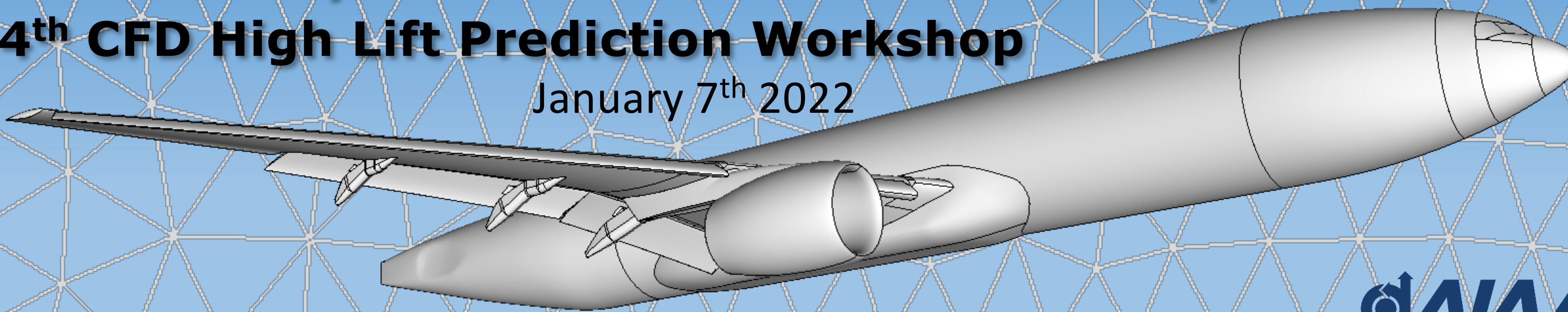
3rd Geometry and Mesh Generation Workshop
4th CFD High Lift Prediction Workshop

January 7th 2022



WMLES/LBM Technology Focus Group Briefing

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Special thanks to
- *WMLES/LBM TFG Teams for data submissions*
- *Chris Rumsey (NASA Langley Research Center) for his support during the HLPW4 activities*

Team Details

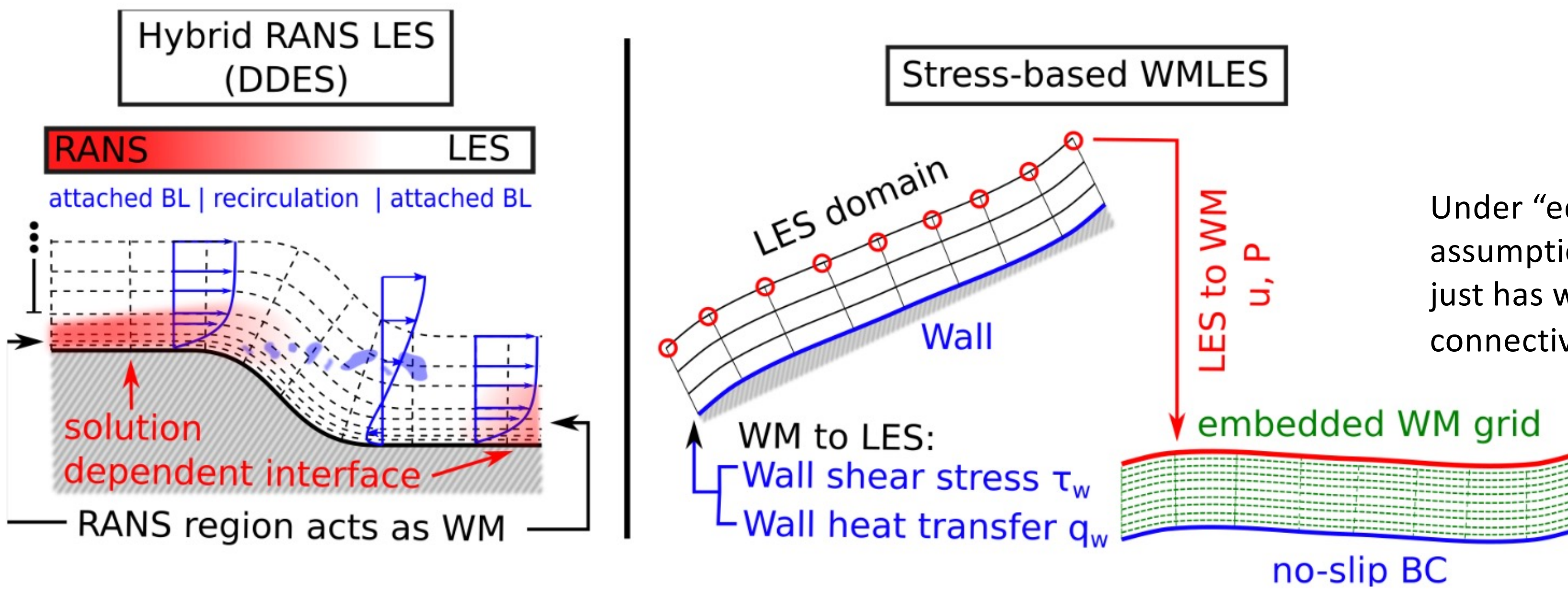
TFG ID (Name)	W (WMLES/LB)
Number of Active Participants	9 teams (~18)
Number of Observers	20+

- Two participants used "committee grids"
- No major changes in geometry definition
- Case 1a/b – Flap Deflection Study
- Case 2a - C_{lmax} Study Free Air
- Case 2b - C_{lmax} Study In Tunnel

			Cases						Grid Used
Group ID	Members (Org)	Tools	1a/b	2a	2b	Time Integration	Spatial discretization	Grid Topology	Committee (C) Self (S)
W-020	NASA ARC	LAVA		x	x	RK3	4th/2nd order finite difference	Structured overset	S
W-021	Stanford & Cascade Tech	charLES		x	x	RK3	2nd order finite volume	Voronoi unstructured	S
W-030	KTH	Real Flight Simulator 2021.01		x		Implicit	finite element	Unstructured adaptive mesh	C
W-031	Boeing	BCFD Version 8r2		x		Implicit BDF2	blended 2nd order finite volume	Unstructured	S
W-032	Dassault Systèmes	PowerFLOW 6-2021	x	x	x	Explicit LBM		Cartesian	S
W-034	Barcelona Supercomputing Center (BSC) & MIT	Alya		x		RK3 conv implicit CN viscous	2nd order finite element	Unstructured	S
W-047	University of Kansas	hpMusic		x		Implicit BDF2	p2 flux reconstruction	Unstructured	C
W-049	Tohoku University	FFVHC-ACE		x		RK3	KEEP	Cartesian	S
W-050	NASA LaRC	FUN3D		x		Implicit BDF2	2nd order finite volume	Unstructured	S

Terminology

- **Equilibrium WMLES: Tangential gradients of pressure and convective stress are assumed to be in exact balance (instantaneously). This eliminates wall-parallel connectivity, and the wall-model can be posed as an ordinary differential equation in wall-normal coordinate exclusively. All participants used Equilibrium wall-modeling.**



Under “equilibrium” assumption this grid just has wall-normal connectivity

Terminology

- **LES**: Large Eddy Simulations; grid scale is used as the filter length scale since no participant is using explicit filtering
- **Subgrid scale (SGS) modeling**: Closure model used to capture effect of unresolved scales on the large resolved scales. All participants are using either a) eddy viscosity closures (purely dissipative SGS), or b) no SGS model with numerical dissipation serving as an SGS model (implicit LES).
- **Wall-model/Wall-function**: Model used to approximate the wall-stress using the solution at a certain distance from the wall. The wall-stress is either directly applied as a stress BC or interpreted via numerical discretization. Most participants are using an algebraic model that requires a Newton solve, while one participant is using an ODE-based model which requires a tridiagonal solve.
- **Exchange location**: The distance from the wall where the solution is interpolated as an input to the wall model. All participants are using a distance between 0.5Delta – 2Delta. None of the participants use any time filtering of the LES solutions prior to its use in the wall-model.
- **Numerical transition**: WMLES that relies on development of boundary layer instabilities to capture laminar to turbulent transition with a turbulent boundary layer assumed everywhere. This transition treatment can be grid-size, numerical discretization and SGS closure dependent with some sensitivity to grid refinement expected. For low Reynolds numbers, it is often preferable to "numerically trip" the flow using either an obstacle or via suction/blowing.

WMLES/LB Details

TFG Name	WMLES/LB
Number of Active Participants	9 teams (~18)
Number of Observers	20+

Submission ID	SGS Closure + Transition	Timestep (non-dim)	Mesh points/DoF (best practice)	Wall-normal grid spacing (Δ)*	Aspect Ratio**	WM – exchange location
W-020	Vreman SGS + Equil. WM	3.3e-5	360M, Structured overset	2.5mm (up to 10%c); 5mm (after 10%c)	Min 1; Max 4; Nominally 2-3	2nd off-wall point (2Δ)
W-021	dyn. Smag. + Equil. WM	5.7e-5	362M, Voronoi unstructured	3.4mm (up to 25%c); 6.8mm (after 25%c)	1	1st off-wall point (0.5Δ)
W-030	Euler + Implicit LES + Inviscid Wall	2.1e-2	3M, Unstructured adaptive mesh	Not available	Min 10; Max 14	Not applicable
W-031	Vreman SGS + Equil. WM	5.8e-4	296M, Unstructured	1.27mm (after 10%c)	Min 10; Max 16	4th off-wall cell (3.5Δ)
W-032	VLES (k-ϵ HRLES) + pressure aware algebraic WM (Equil.)	3.7e-5	475M, Cartesian	Approx. 10mm	1	0.5Δ
W-034	Vreman SGS + Equil. WM	2.9e-5	273M, Unstructured	7mm (Voronoi); 0.8mm (Hex)	1 for Voronoi; 1-30 for Hex	2nd off-wall point for Voronoi; 3rd off-wall point for Hex
W-047	implicit LES + Equil. WM	9.7e-5	13M, Unstructured	7.2 mm (21.5/3 mm)	Min 1; Max 71	Interface between the 1st and 2nd elements
W-049	CSM + Equil. WM	3.6e-5	1.12B, Cartesian	3.2mm	1	3.5Δ off-wall
W-050	Vreman SGS + Equil. WM	5e-4	419M, Unstructured	3.3mm		1st off-wall point (1Δ)

*assuming full scale geometry with 7m MAC **representative number given by participants. Typically, represents the ratio of tangential spacing to wall normal spacing

WMLES/LB Data Submissions

Submission ID	Integrated loads (CL, CD, CMY)	Load History	CP slices	Vorticity Planes	Surface CF & Streamlines	Unsteady Pressure	Velocity Profiles	Computational Cost
W-020	YES	YES	YES	YES	YES	YES	YES	YES
W-021	YES	YES	YES	PARTIAL	YES	NO	NO	YES
W-030	YES	YES	YES	NO	PARTIAL	NO	NO	YES
W-031	YES	YES	YES	YES	YES	NO	YES	NO
W-032*	YES	YES	YES	YES	YES	YES	YES	YES
W-034	YES (missing CMY)	NO	YES	NO	YES	NO	NO	YES
W-047	YES	YES	YES	YES	PARTIAL	NO	YES	YES
W-049	YES	NO	YES	YES	YES	NO	YES	YES
W-050	YES	NO	YES	NO	NO	NO	NO	NO

*Also submitted results for Case 1b (flap deflection study). Will be reported in the HLPW4 summary presentation

WMLES/LB Key Questions

#	Key Question	Addressed By Which Groups (GID)	Adequately answered with supporting evidence?
1	How sensitive are the integrated forces and moments (e.g. lift, drag, pitching moment coefficients) to the computational grid? (a) Will we be able to show convincing convergence with respect to the grid? (b) Can we define a credible process for verifying that the results are sufficiently converged, and what exactly would that process be?	All Grid resolution studies by W-020, W-021,W-034	Yes
2	With the fuselage mounted on the tunnel wall, how important is it to characterize the tunnel boundary layer?	W-020, W-021, W-032	Partial
3	What are the factors limiting accuracy and/or computational cost, and what is the estimated gain (in accuracy and/or cost) from improvements to each factor?	Majority	Partial
4	Relevance of tripping used on the wing. Does tripping need to be explicitly represented, or numerical transition is sufficient?	All	Partial
5	How do we handle the very thin boundary layer at the leading edge in a sufficiently accurate yet affordable manner?	None	No
6	Will some kind of implicit time-stepping be necessary at realistic Reynolds and Mach numbers?	W-031,W-047, W-050	Partial

Key Findings / Lessons Learned

KQ # 1	**How sensitive are the integrated forces and moments (e.g. lift, drag, pitching moment coefficients) to the computational grid? (a) Will we be able to show convincing convergence with respect to the grid? (b) Can we define a credible process for verifying that the results are sufficiently converged, and what exactly would that process be?**

Key Findings

- Large sensitivity to grid resolution particularly at CLmax and post-stall seen. CL convergence seems much easier than CMY convergence – current results show reasonable convergence in CMY.
- Sensitivity in pitching moment seen at both lowest (flap heavily loaded) and highest angle (outboard wing heavily loaded). Due to large geometric curvature, particularly in the outboard section of the wing, there is significant sensitivity to streamwise grid spacing.
- Three participants were able to test grid convergence in the free air case and one in the wind tunnel case.
- For high AoA cases, it required to run long time to make sure flow patterns do not change and stationarity is achieved.

Lessons Learned

- Grid resolution studies could be prohibitively expensive due to timestep size.
- Grid quality and numerical dissipation played important role.
- Need to emphasize grid convergence in terms of CMY instead of CL.
- Isotropic grids have advantages and disadvantages over anisotropic grids that need to be systematically investigated.

Key Findings / Lessons Learned

KQ # 2	With the fuselage mounted on the tunnel wall, how important is it to characterize the tunnel boundary layer?

Key Findings

- Three participants ran the wind tunnel simulations at all alphas. All three WMLES entries for WT simulation show excellent agreement with wind tunnel data. WMLES was far superior at predicting the aerodynamic loads when compared to RANS wind tunnel simulations.
- Importantly, three LES SGS closures with various grid and discretization strategies predict the correct stall mechanism (loads, moments, cp, surface streamlines) for the correct reasons.
- There is less scatter between the WMLES in-tunnel results than was seen in the free air case.
- No participant was able to produce the tunnel boundary-layer in agreement with the rake measurements. Regardless of the differences reported in the boundary-layer profiles between WMLES and wind tunnel, both the stall-mechanism and stalled state-showed excellent agreement with wind tunnel measurements.
- At post CLmax stall AoA, the surface flow topology appeared to be rather insensitive to treatment of tunnel walls (viscous vs slip BC). This was demonstrated independently by two participants. Moderate sensitivity to tunnel wall BCs was observed in pitching moment at AoA's before the stall.

Lessons Learned

- Further investigations are needed to understand competing roles of tunnel BL, standoff-height and tunnel blockage.
- More accurate tunnel measurements are needed to reproduce the wind tunnel experiments i.e. unsteady pressure, boundary layer in multiple locations. Sting-mounted (full model) testing is preferred for future studies and would eliminate many uncertainties.

Key Findings / Lessons Learned

KQ # 3	What are the factors limiting accuracy and/or computational cost, and what is the estimated gain (in accuracy and/or cost) from improvements to each factor?

Key Findings

- While a typical WMLES is more expensive than steady-state RANS simulations, WMLES provides accurate and consistent predictions while steady-state RANS has been proven to be unsuitable for flow regimes dominated by large scale separation i.e. CLmax and stall.
- Many teams pointed out that time/space resolution have been essential to reach accurate solutions (high AoAs).
- Simulation time: lots of CTUs needed for highest angles.
- High geometric curvature, particularly towards the outboard wing, necessitates a minimum threshold for required degrees of freedom - most accurate WMLES predictions of outboard flow required a mesh with dof>250M.
- Low geometric Reynolds for outboard wing and/or flaps exaggerates the importance of thin transitioning boundary layers and affects pitching moment predictions at both highest and lowest angles of attack.

Lessons Learned

- Explicit time stepping formulations show very promising scalability with wall-times that are very competitive with RANS.
- Automated mesh generation and extensions to GPU are demonstrated by multiple participants.

Key Findings / Lessons Learned

KQ # 4	Relevance of tripping used on the wing. Does tripping need to be explicitly represented, or numerical transition is sufficient?

Key Findings

- Almost every team relied on numerical transition. Some used physical tripping but scaled size tripping (not actual size).
- One participant investigated tripping via 2x taller than experimental trip dots. While a more regular transition pattern was observed when obstructive tipping was used it did not appear to have an affect the on the integrated quantities.

Lessons Learned

- An exact representation of physical tripping is prohibitively expensive in WMLES – more computational resources needed to fully investigate. This might be pertinent to investigating the separation on the nacelle.

Key Findings / Lessons Learned

KQ # 5	How do we handle the very thin boundary layer at the leading edge in a sufficiently accurate yet affordable manner?

Key Findings

- None of the WMLES/LBM group tried to attack this problem. Almost every team used no-special treatment (all wall models assumed turbulent boundary-layers globally) at the leading edge, although preventing spurious oscillations at large pressure gradients seems important.

Lessons Learned

- WMLES wall normal spacing does not allow for a large number of grid points to resolve the boundary layer at the leading edge. It is a difficult key question to investigate.

Key Findings / Lessons Learned

KQ # 6	Will some kind of implicit time-stepping be necessary at realistic Reynolds and Mach numbers?

Key Findings

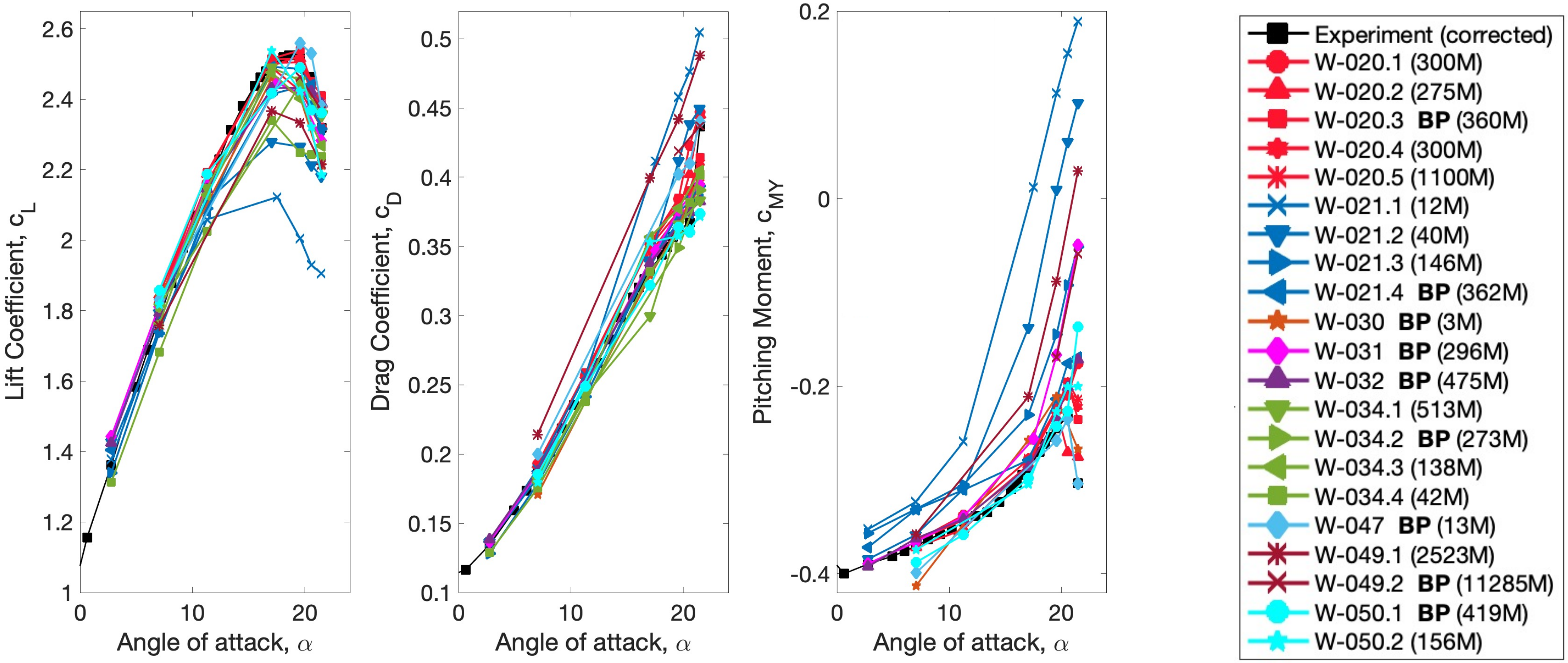
- This key question has not been addressed directly. Many WMLES schemes used explicit time-integration methods. Teams W-030, W-031, W-047, W-050 used implicit time-integration in order to run on arbitrary grids.

Lessons Learned

- Majority of teams using more isotropic grids used explicit time-integration. Some focused on the effect of the numerical sensors. Teams using implicit methods indicated that they can not run explicit time-integration on the grids they have been using due to grid quality, grid aspect ratio, etc. related issues.
- Implicit time integration could enable resolution of laminar BLs, benefit/complications of doing that was not addressed. This is also related to key question #5.

Integrated Loads

All Submissions – Free Air (case2a)



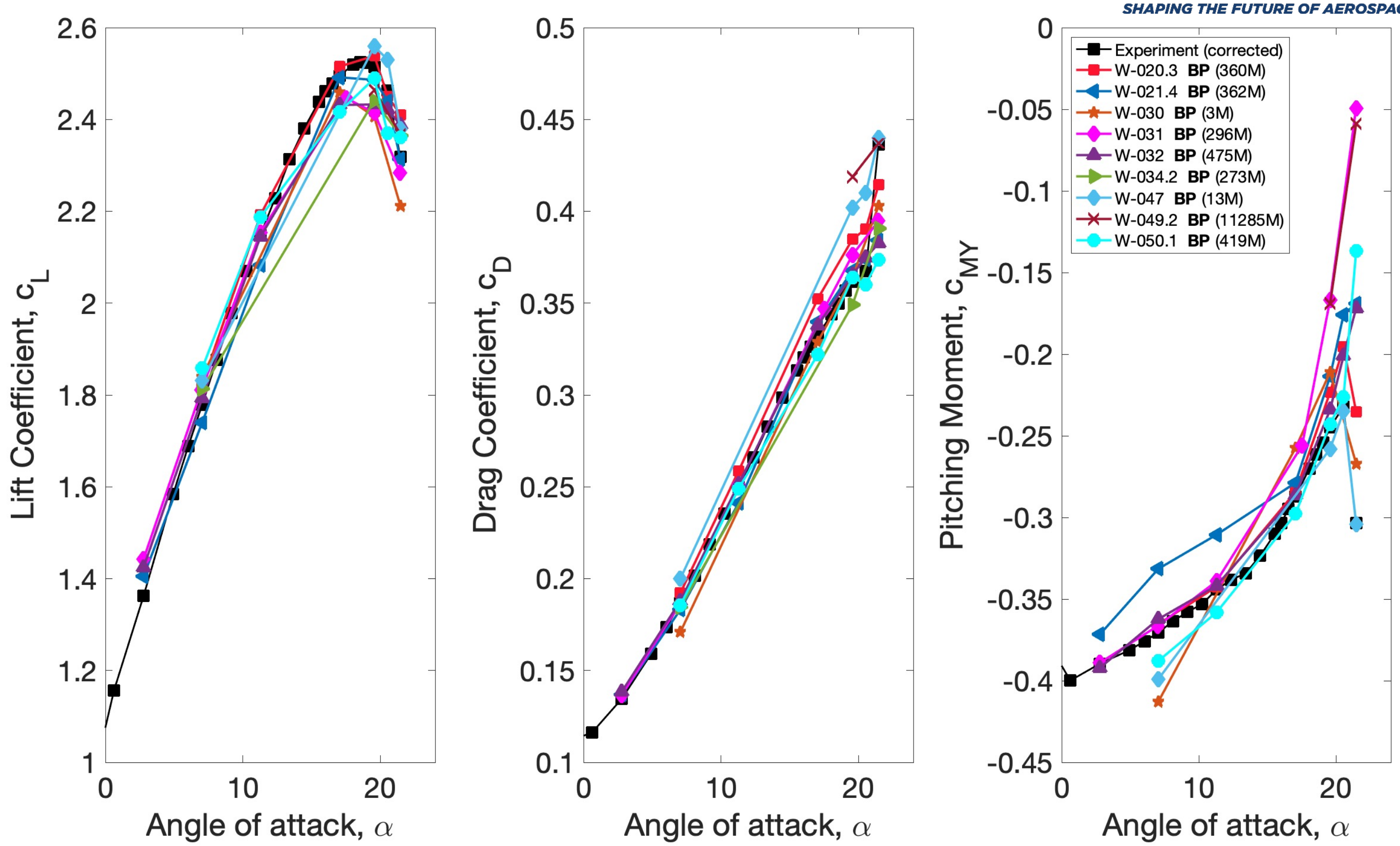
Integrated Loads

Best Practice Only – Free Air (case2a)

AIAA SHAPING THE FUTURE OF AEROSPACE

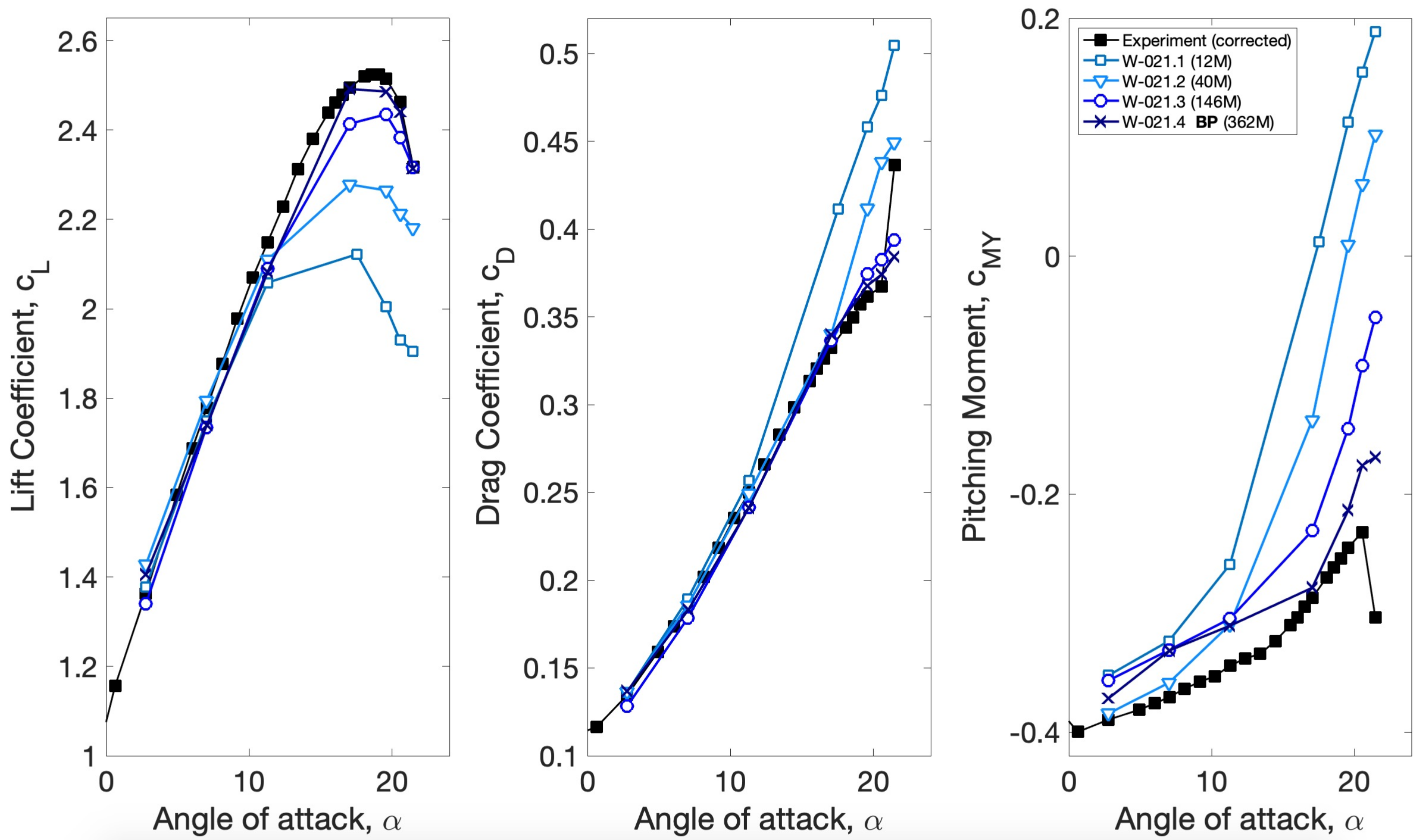
To establish integrated loads credibility, the following needs to investigated:

1. Grid convergence or sensitivity to grid
2. Stationarity of the loads history



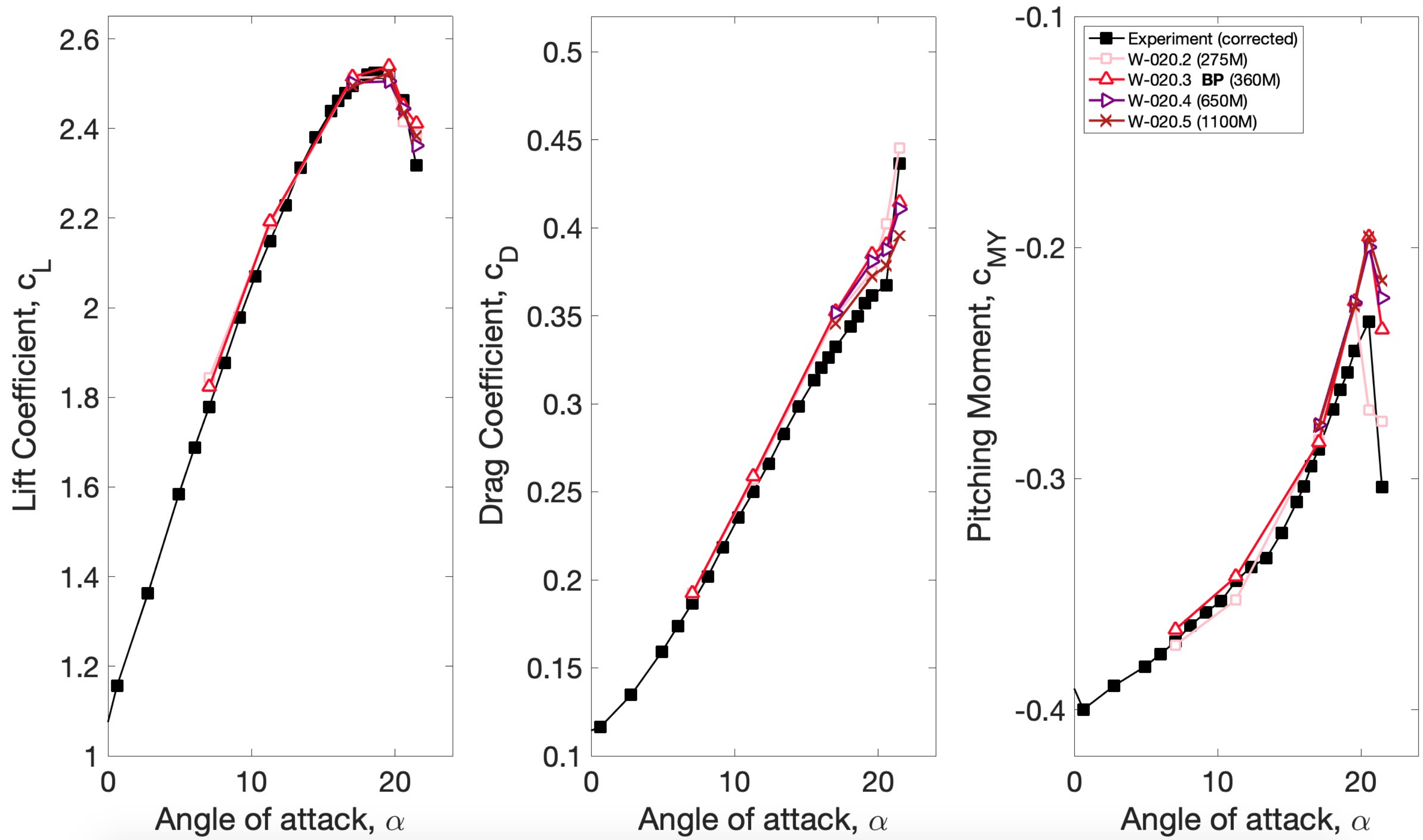
Integrated Loads

Grid Convergence Studies – Free Air (case2a) – W-021

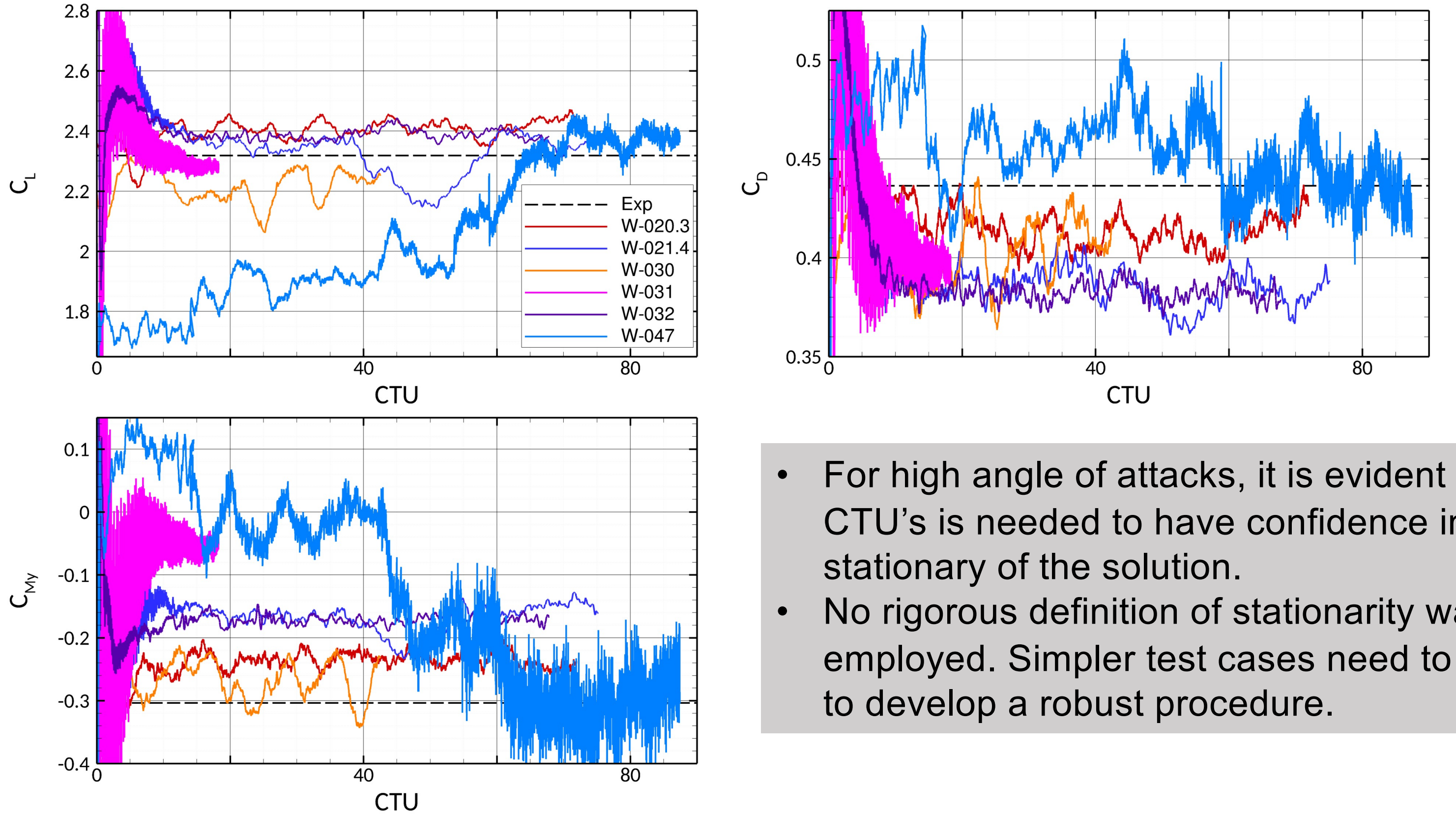


Integrated Loads

Grid Convergence Studies – Free Air (case2a) – W-020



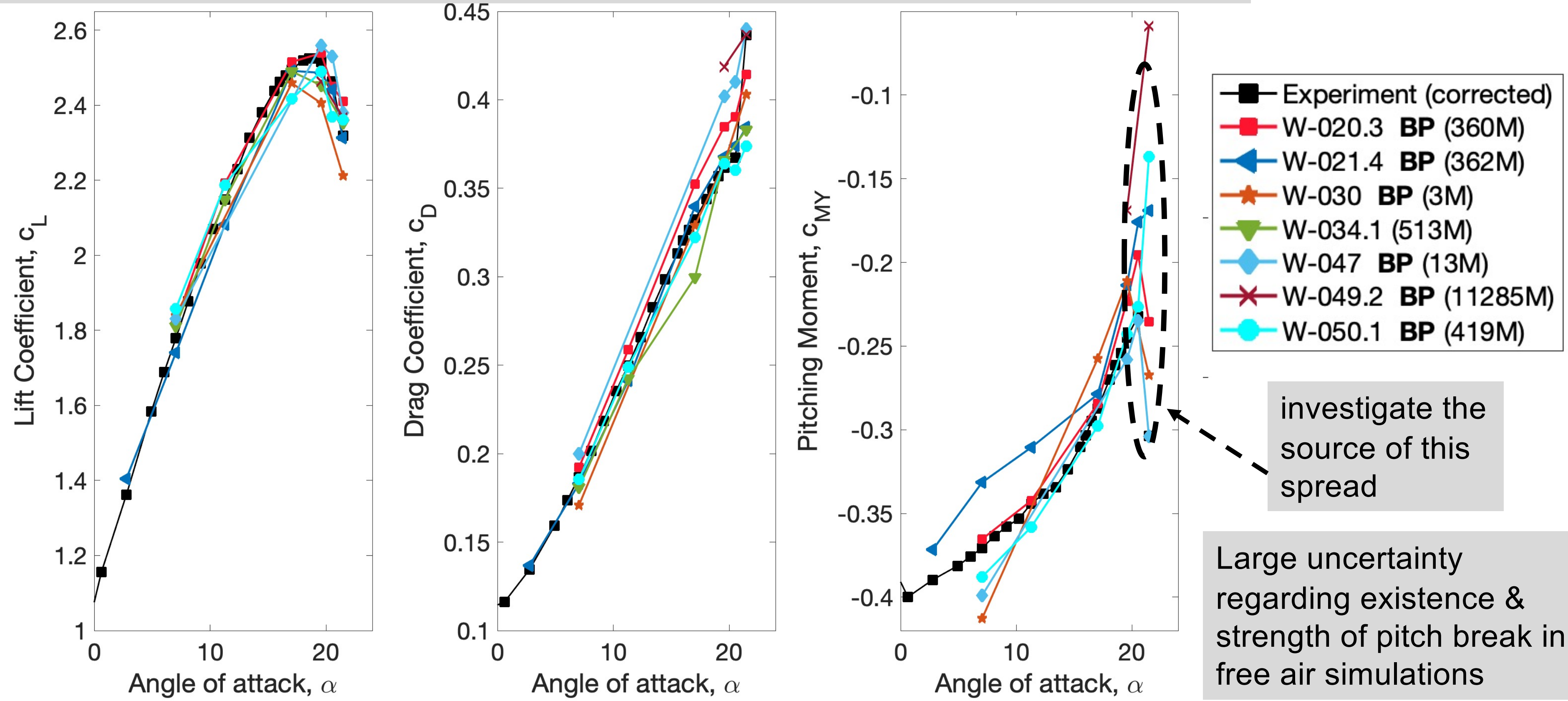
Stationarity of the Load History at 21.47°



- For high angle of attacks, it is evident that >70 CTU's is needed to have confidence in the stationary of the solution.
- No rigorous definition of stationarity was employed. Simpler test cases need to be utilized to develop a robust procedure.

Integrated Loads

Error metric (+/- 2%) at CLmax (17.05° or 19.57°) - Free Air (case2a)

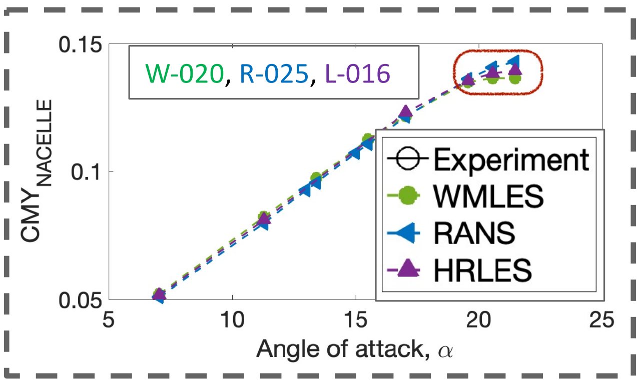


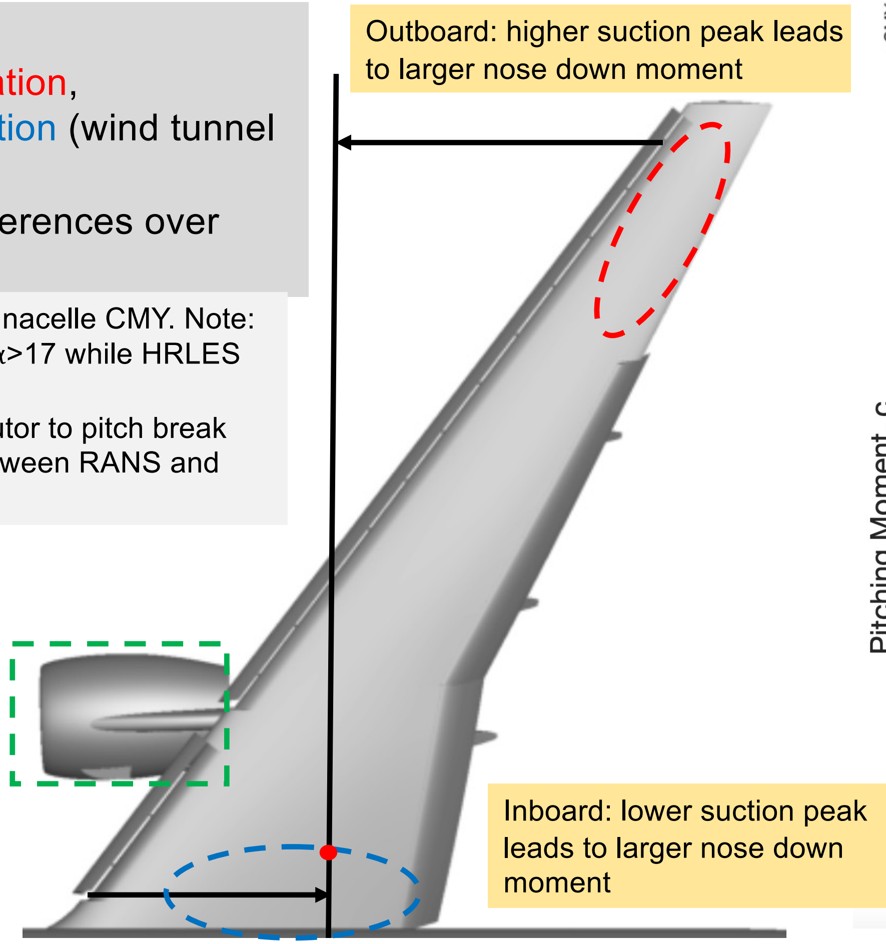
Moment Balance for Pitch Break

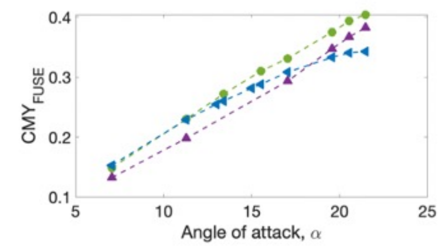
CFD will not predict a pitch break if:

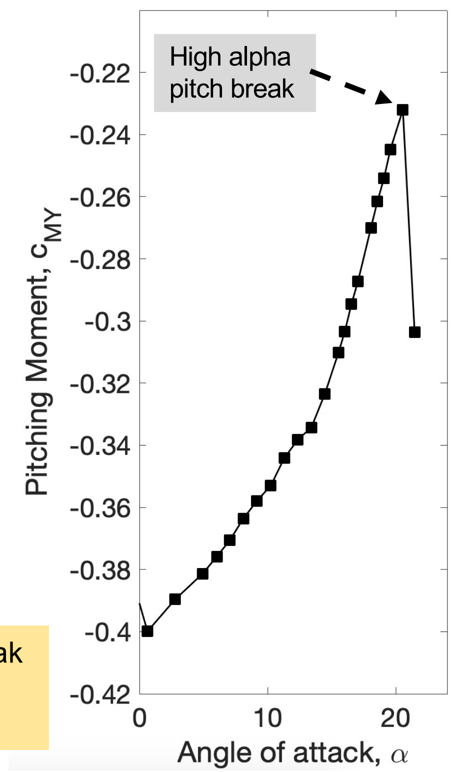
- It predicts excessive outboard separation,
- It does not produce wing-root separation (wind tunnel installation effects could play a role).
- Need to emphasize flow topology differences over integral values

- Nacelle separation does not appear to influence nacelle CMY. Note: WMLES + RANS predict nacelle separation for α>17 while HRLES does not.
- Fuselage does not appear to be a major contributor to pitch break discussions based on the CMY comparisons between RANS and WMLES (see AIAA-2022-1554).

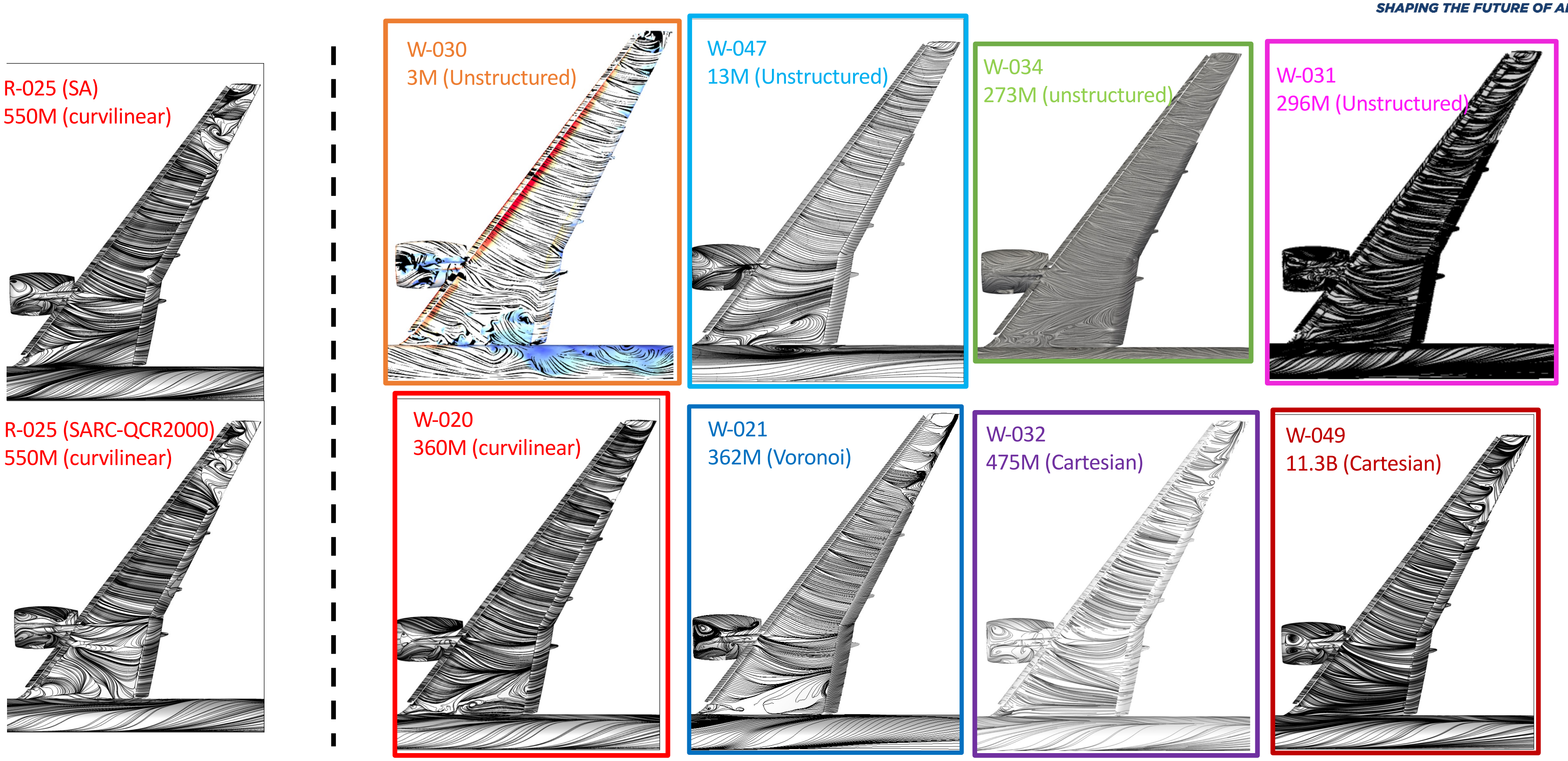




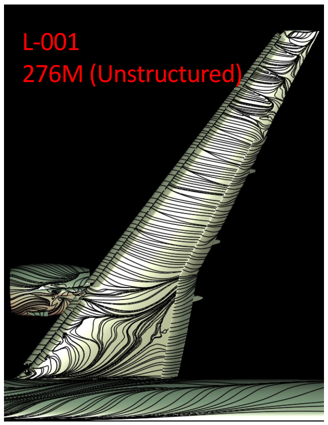


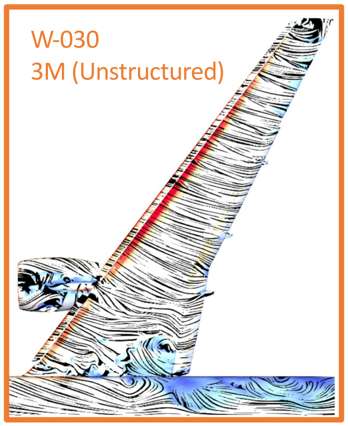


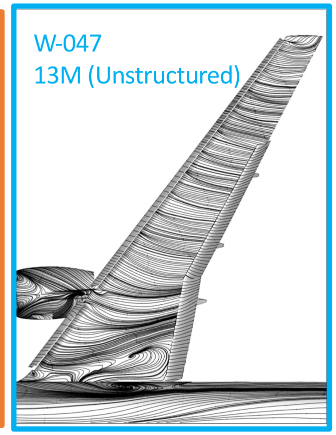
WMLES vs RANS at 21.47°

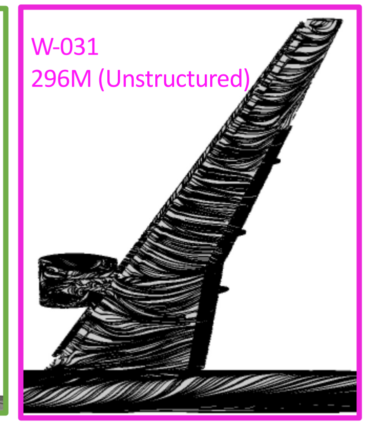


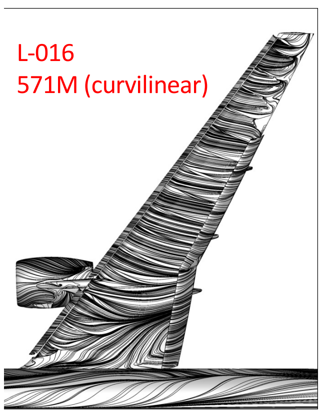
WMLES vs HRLES at 21.47°

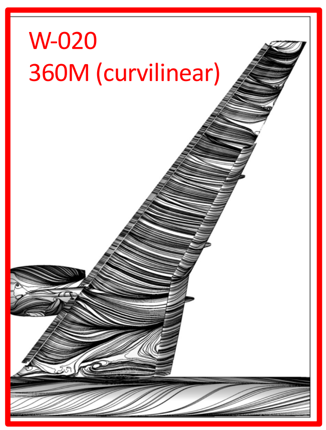


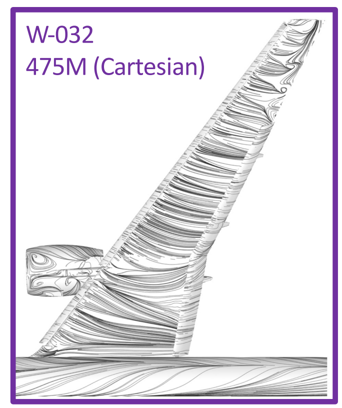




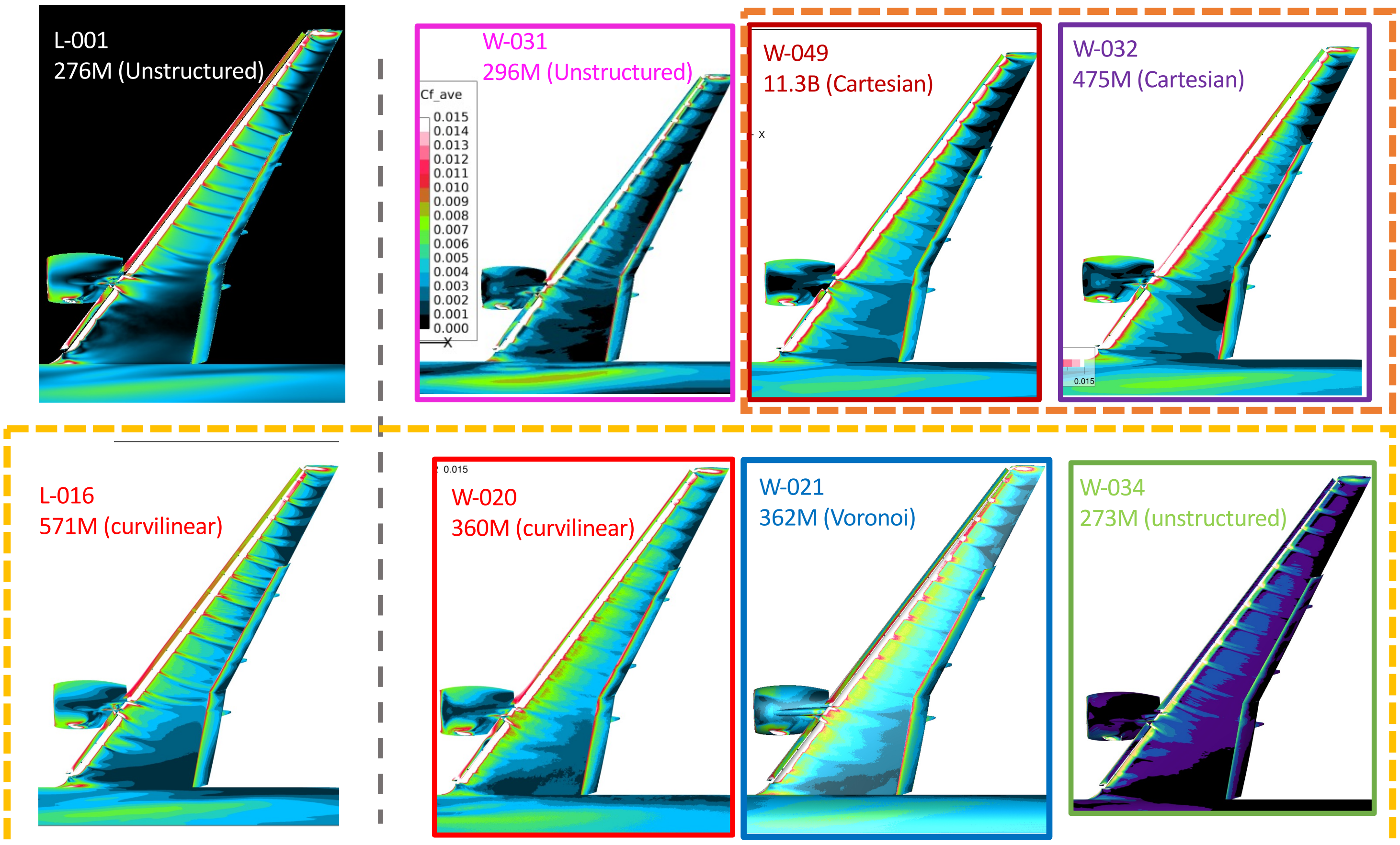








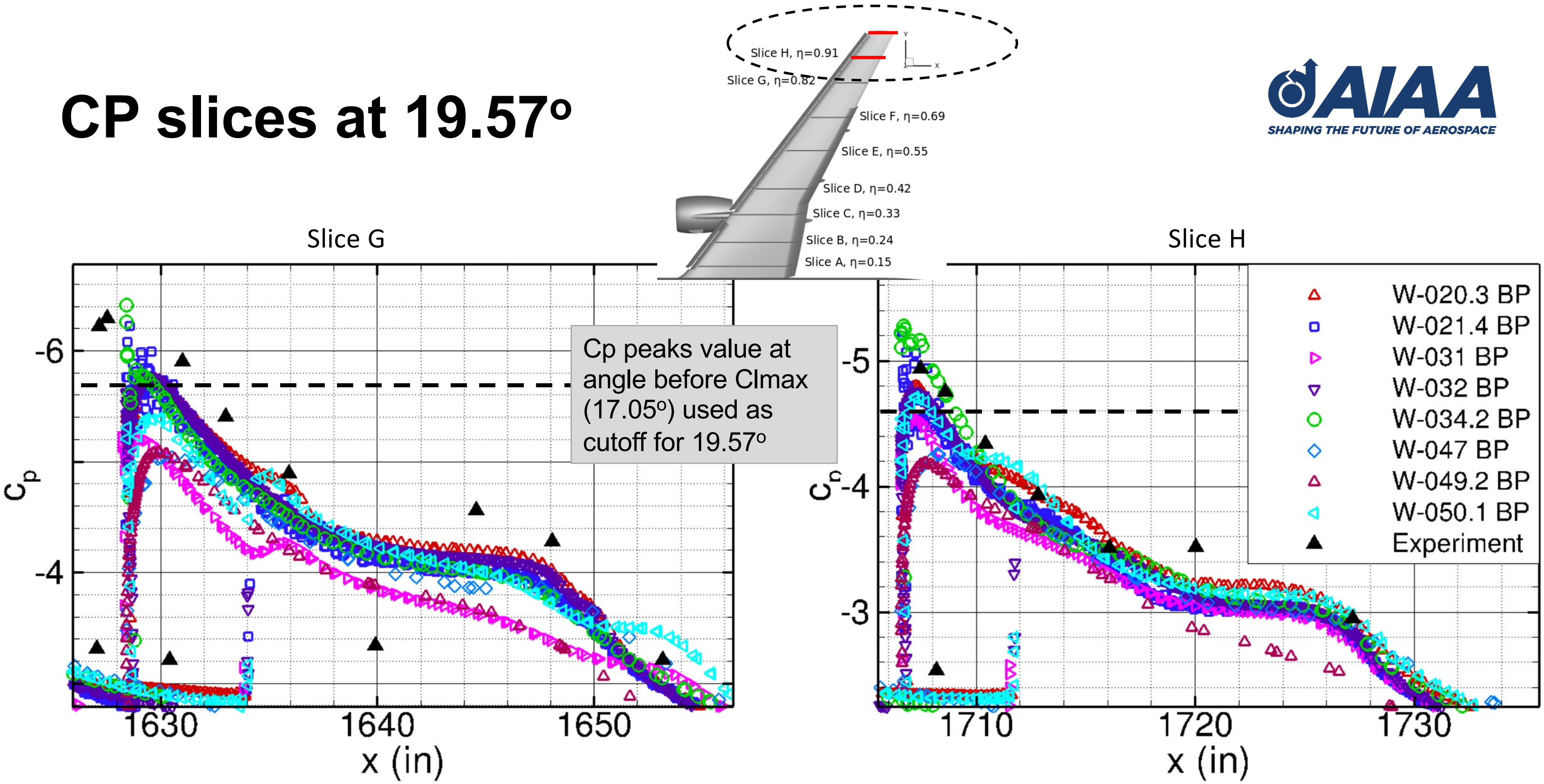
WMLES vs HRLES at 21.47°



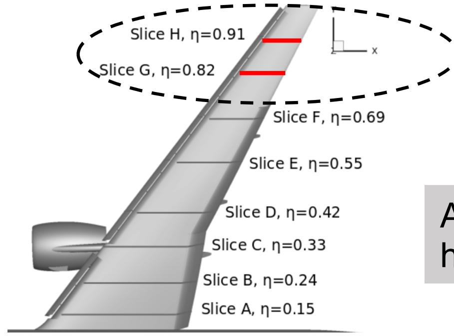
W-030, W-047 and W-050 did not submit CF contours.

Similar inboard flow topologies are isolated in the two boxes.

CP slices at 19.57°

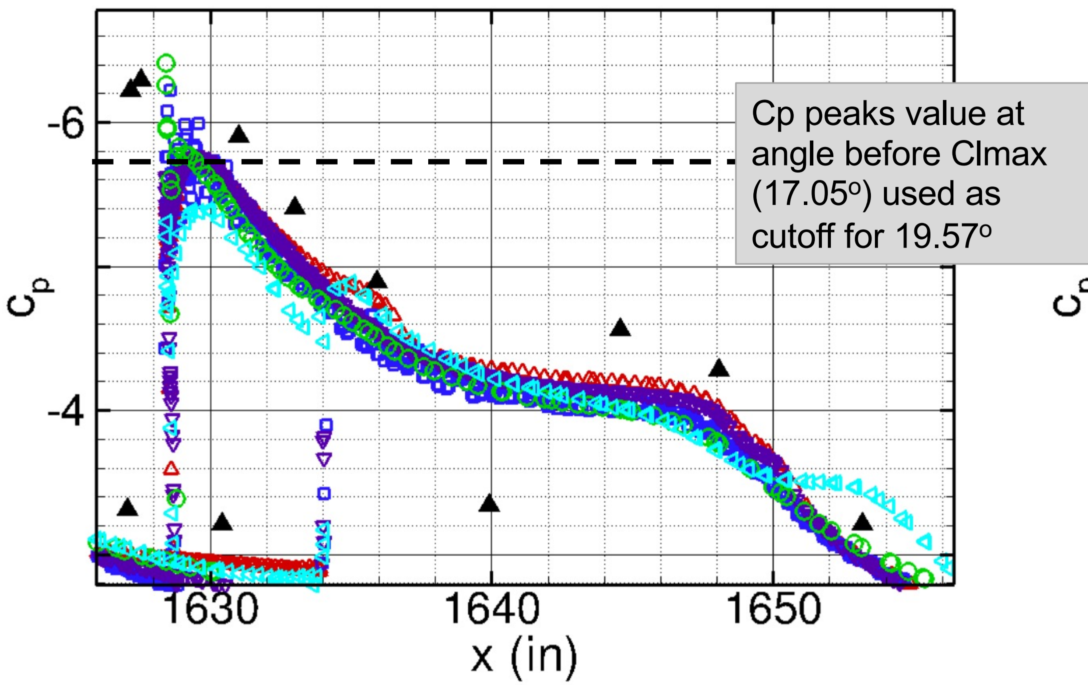


CP slices at 19.57°

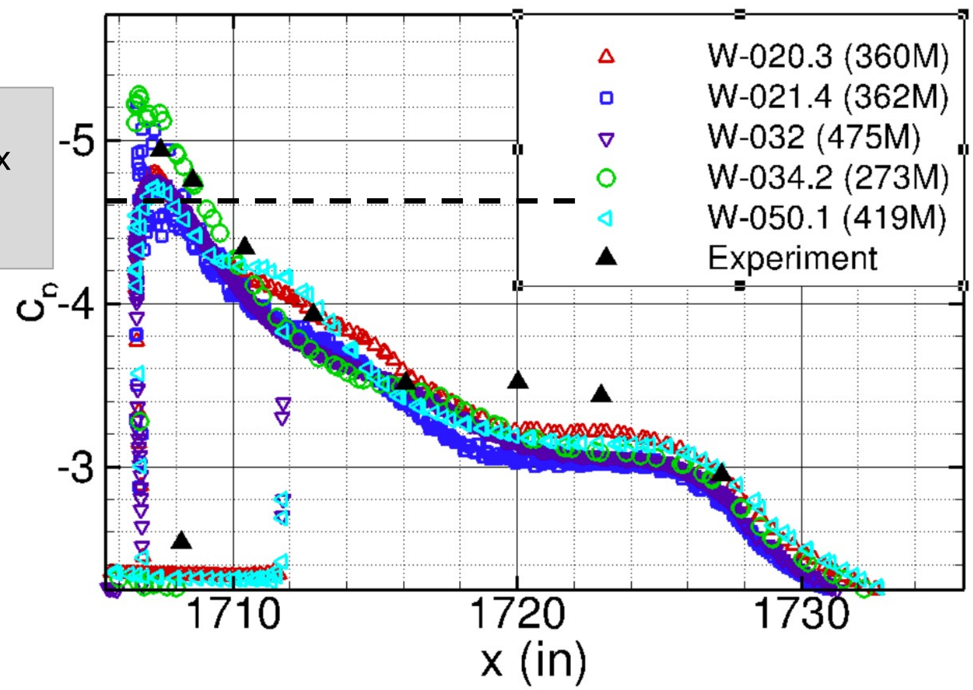


All those that had the specified accuracy have >250M grid points!

Slice G

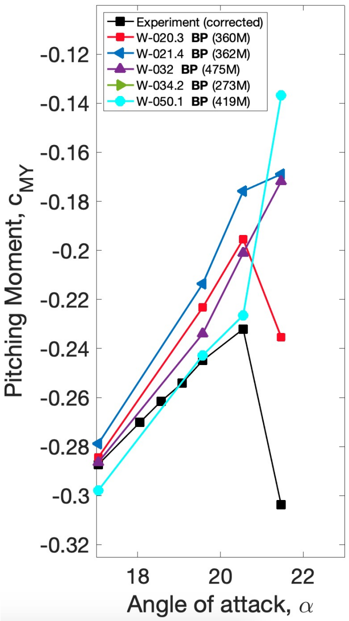


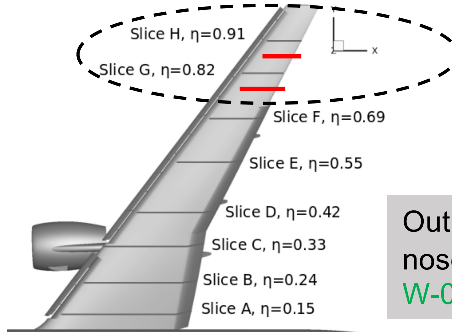
Slice H



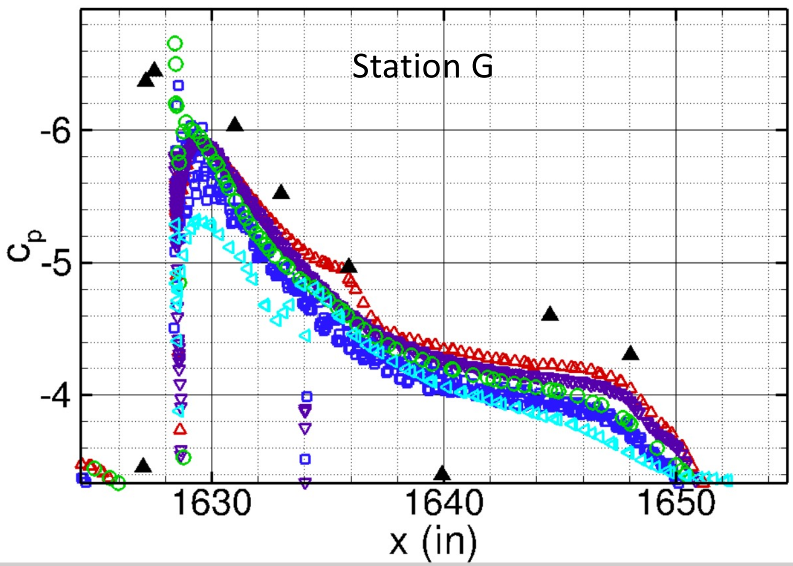
CP slices at 21.47°

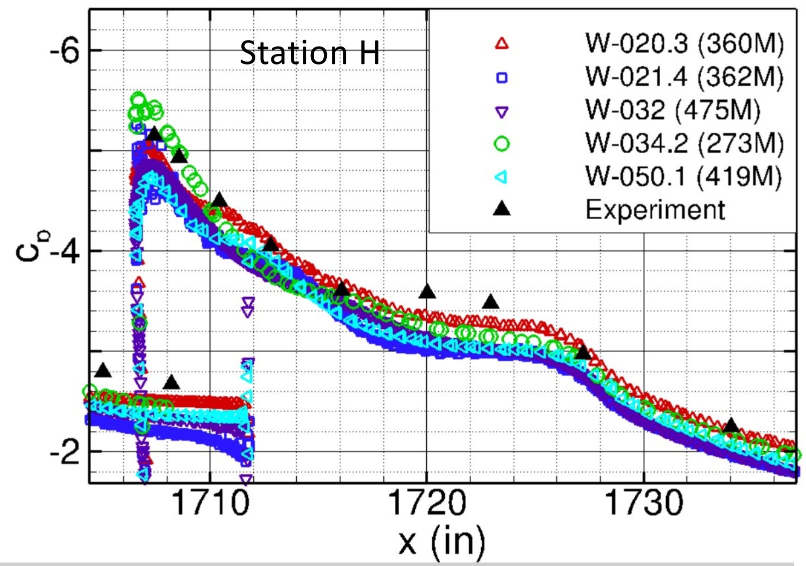
"Pitch break" terminology used to identify changes in dCMY/dα





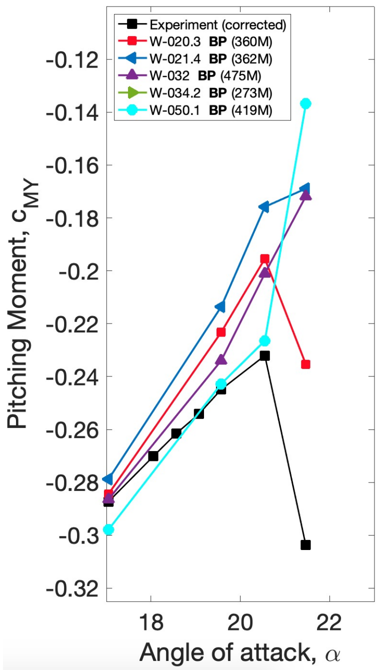
Outboard suction - Higher suction peak leads to larger nose down moment:
W-034 > W-020 > W-032 > W-021 > W-050

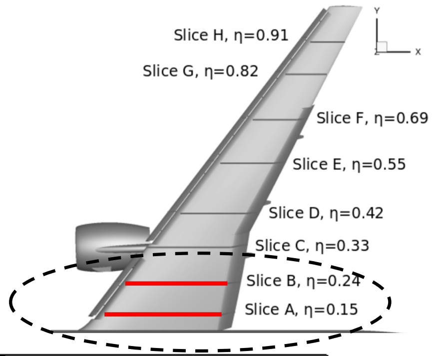


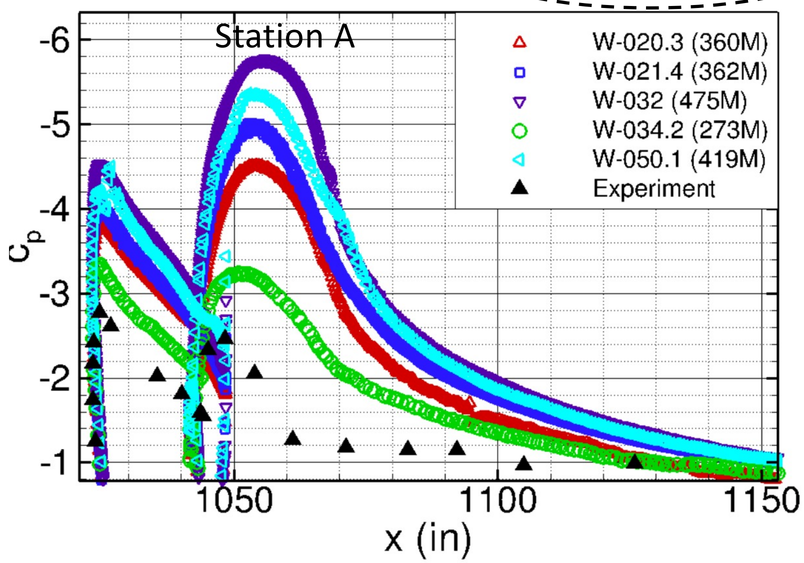


Comparison of outboard suction peak and respective pitching moments.
W-020 – drop in pitch moment, W-021 - drop in pitch moment slope, W-032 negligible change in pitch moment slope, W-034 - did not provide CMY, W-050 – increase in pitch moment slope

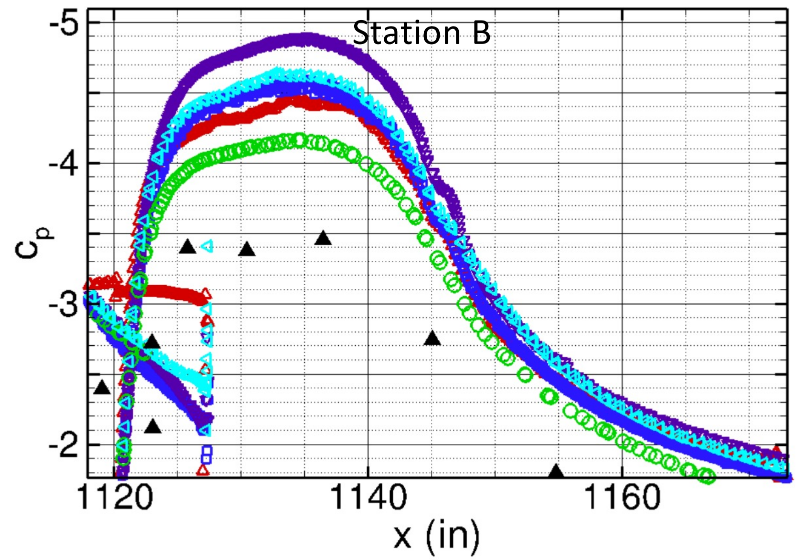
CP slices at 21.47°







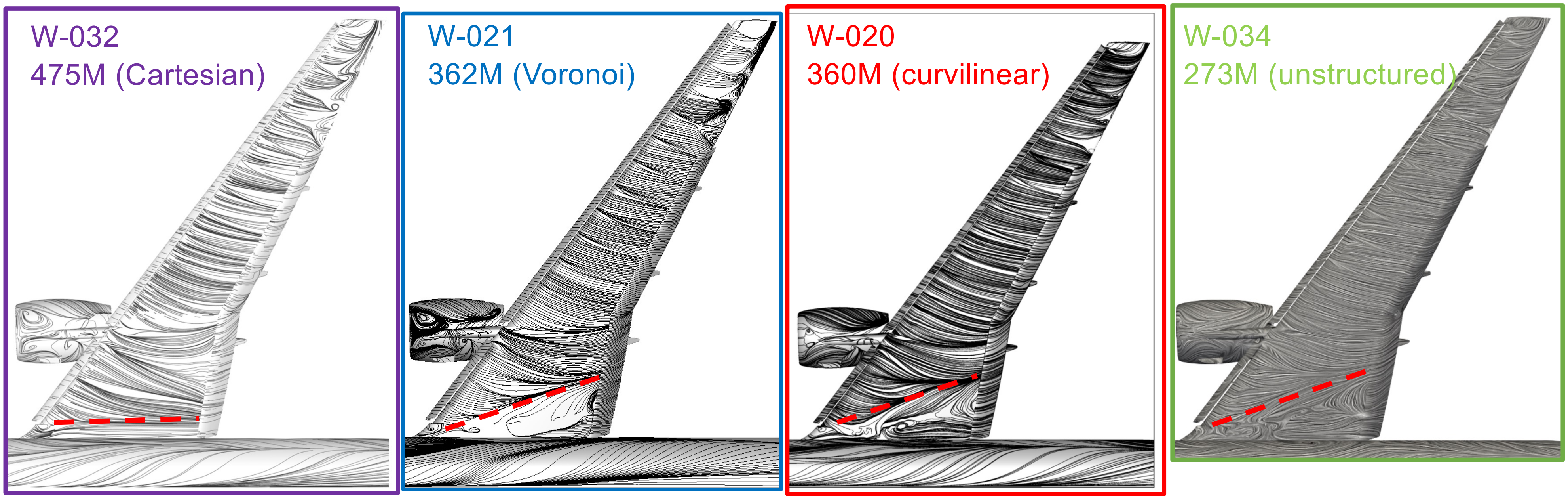
Loss of inboard suction – excessively high suction peak leads to larger nose up moment:
W-032 > W-050 > W-021 > W-020 > W-034



Comparison of inboard suction peak and respective pitching moments.
W-020 – drop in pitch moment, W-021 - drop in pitch moment slope, W-032 negligible change in pitch moment slope, W-034 - did not provide CMY, W-050 – increase in pitch moment slope

Surface Streamlines at 21.47°

Ordered (→) based on progression of corner flow separation

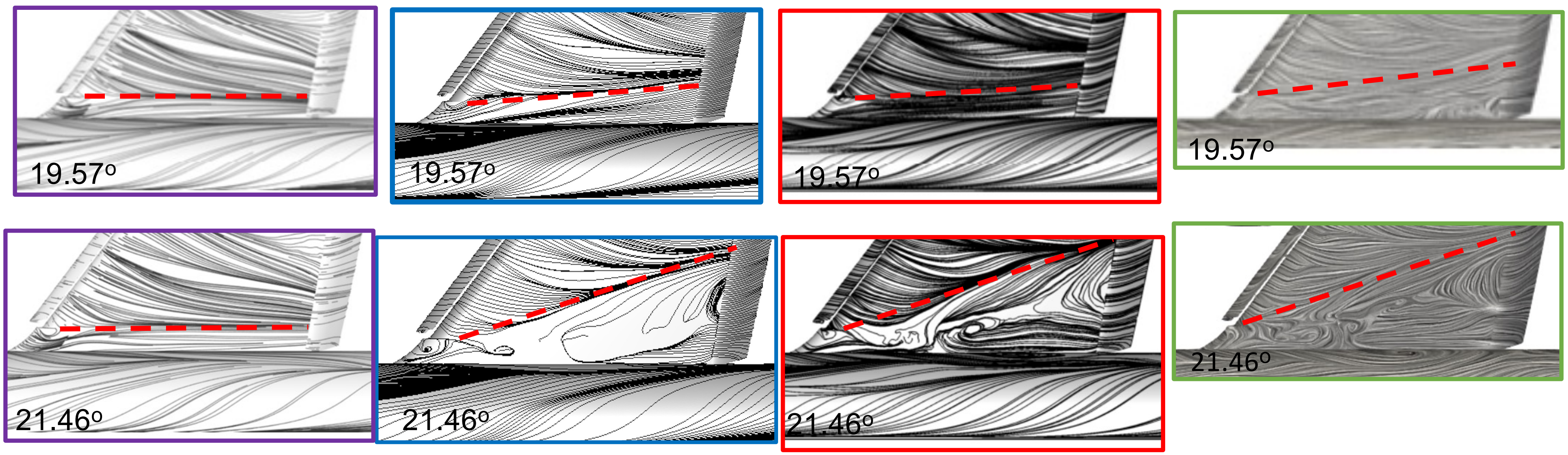


W-050 did not submit streamlines among 5 submissions down selected from Cp

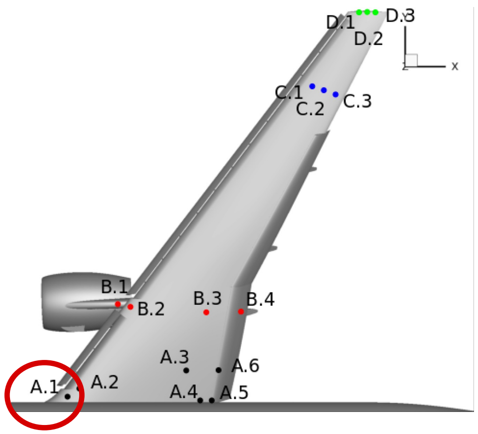
Inboard Flow Topology from 19.57 to 21.47°

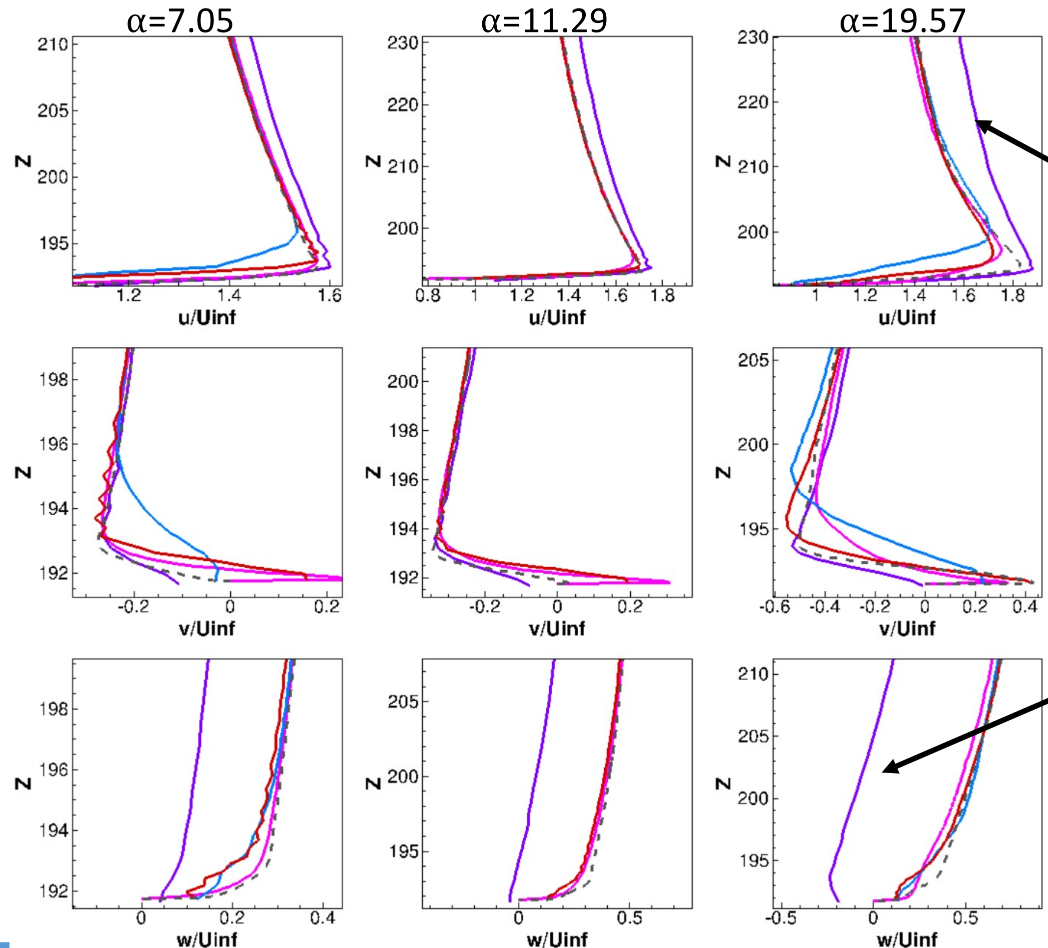
Ordered (→) based on progression of corner flow separation

W-032 475M (Cartesian) | W-021 362M (Voronoi) | W-020 360M (curvilinear) | W-034 273M (unstructured)



Velocity Profiles – A.1





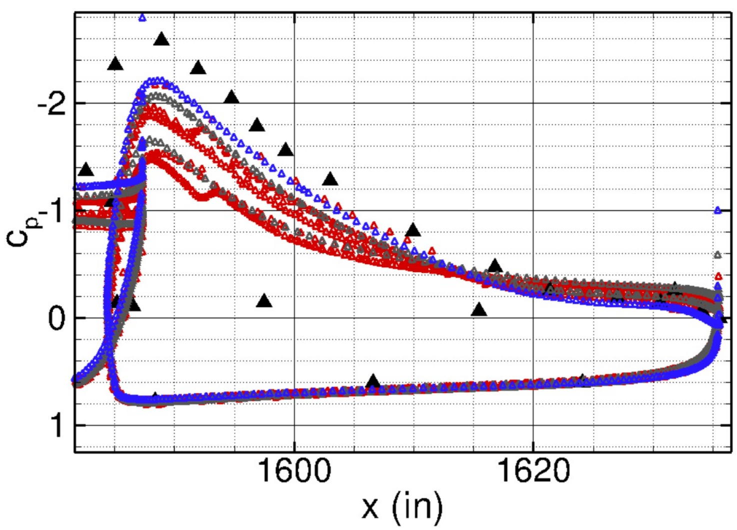
W-020 (solid line)
W-031 (solid line)
W-032 (solid line)
W-047 (solid line)
L-016 (dashed line)

- Offset in u and w velocity components seen in W-032 (across all angles) indicates a lower apparent angle of attack seen at the wing root.
- Could potentially explain the lack of corner flow separation?

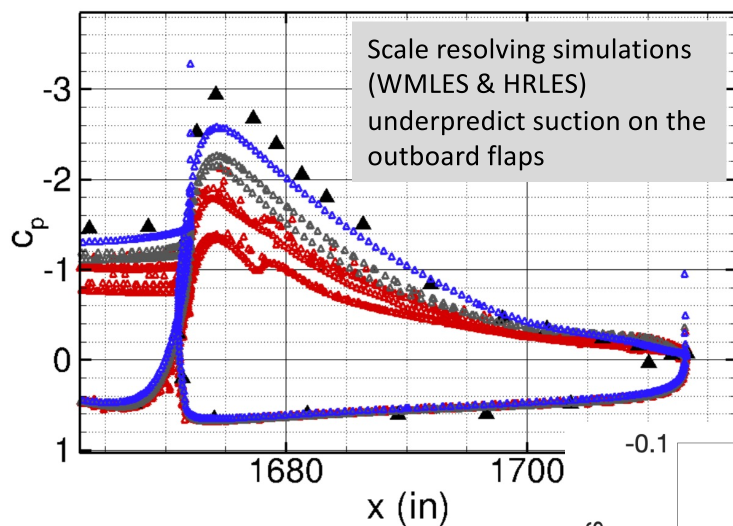
Peculiar Behavior on Outboard Flap for α>15°

α=19.57, WMLES, HRLES, RANS

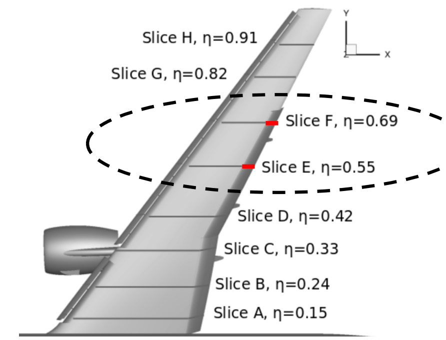
Station E (Flap)



Station F (Flap)



Scale resolving simulations (WMLES & HRLES) underpredict suction on the outboard flaps



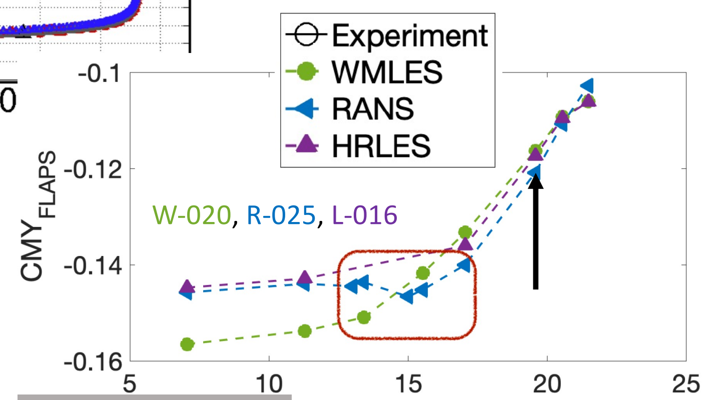


Fig from AIAA-2022-1554

Rapidly diminishing contribution of the nose down moment from the flap for α>15°, downplays the differences in the suction peaks seen on the outboard flaps.

Observations - Free Air

1. Are **Cartesian** grid submissions much more **refined off-body** in comparison to **curvilinear structured** and **anisotropic unstructured** grid?
   - Possibly – might resolve off-body vorticity more accurately which suppresses wing-root separation.

2. Are **curvilinear structured** and **unstructured** grids more boundary-layer refined in comparison to **Voronoi unstructured** and **Cartesian** grid?
   - Possibly – might capture corner-flow (wing-root) and/or smooth-body (outboard wing/flaps) separation physics more accurately.

3. Due to half-span experiment setup – unclear if free-air submissions can be appraised as "more/less accurate" – emphasis was instead placed on identifying similarities/differences among submissions.

4. Based on the outboard topology and pressure coefficients predicted near CLmax, several submissions were identified as having suboptimal discretization and/or space-time resolution.

5. Among the remaining submissions (all with greater than 250M grid points), W-020, W-021, W-034 show corner flow separation (of slightly varying degrees of progression) while W-032 did not. As as result of the corner flow separation, W-020 and W-021 show a change in pitch moment slope between 20.55^{o} and 21.47^{o} while the latter did not. While W-034 did not provide integrated moments, analysis of the pressure coefficient data indicates a similar break in the pitching moment was observed.

Observations - Free Air (continued)

6. Although there were some outliers, WMLES TFG shows more consistency in CLmax predictions than RANS.

7. W-030 shows promise with a rapid LES solution procedure with measurable improvements over RANS but is not representative of typical WMLES due to the assumed Reynolds number invariance (Euler Eqs). The validity of this procedure for high lift applications needs to be investigated more critically. W-030 is also part of the Adapt TFG.

8. While W-047 (also part of HO TFG) who utilized extremely coarse grids showed promising results, the submission was unable to make a case for high-order methods reducing the number of degrees in WMLES.

9. It was difficult to gauge solution trends for participants did not provide either load history or surface flow patterns.

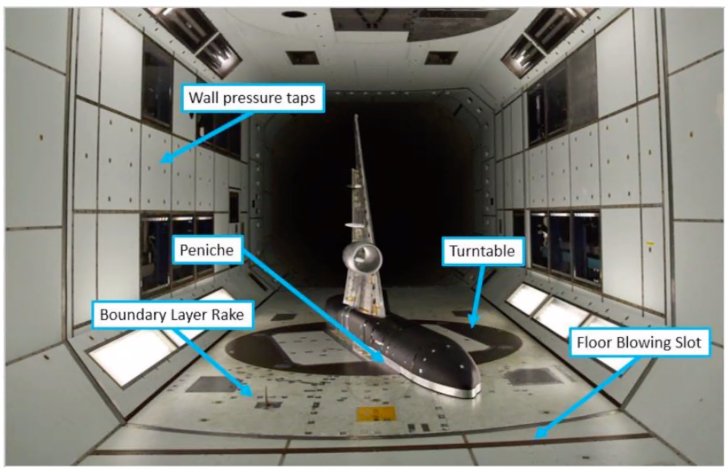
10. Not enough participants provided vorticity data (or unsteady pressures) to draw any meaningful conclusions based on off-body vortex patterns (or pressure spectra).

11. Several challenges (limited submissions from W-020, W-031, W-032, W-047, W-049) associated with velocity profiles restricted the discussion of the data:
    - Turbulent boundary layers profiles at a given location is influenced by its upstream transition – this was not explicitly controlled in any of the submissions.
    - *A priori* determination of time-averaging intervals is not possible and snapshot averaging of volume data (large files, infrequent I/O) is much harder than surface data (small files, frequent I/O).

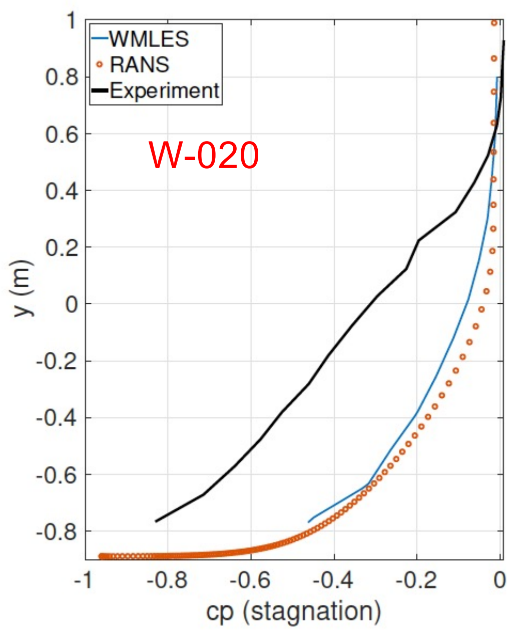
In-Tunnel WMLES (W-020,W-021 and W-032)

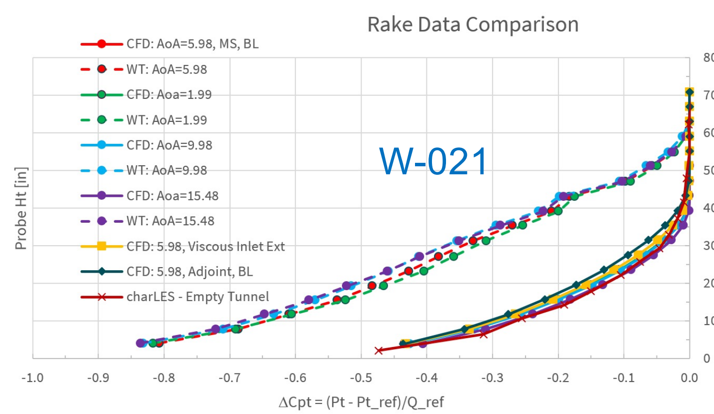
Major sources of uncertainty for wind tunnel CFD simulations:

- Initialization of the wind tunnel
- Boundary layer profile at the tunnel walls



HL-CRM at QinetiQ WT

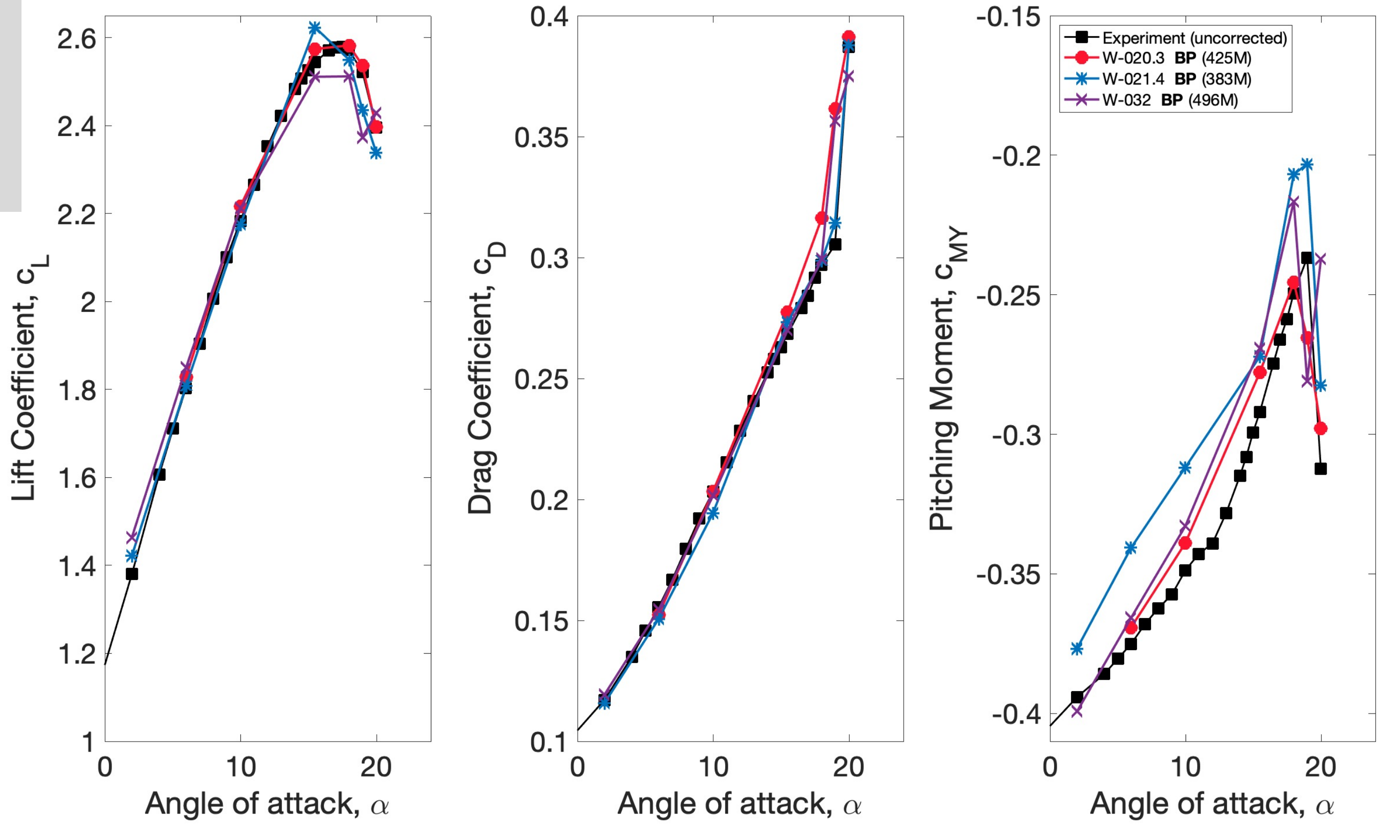




Integrated Loads

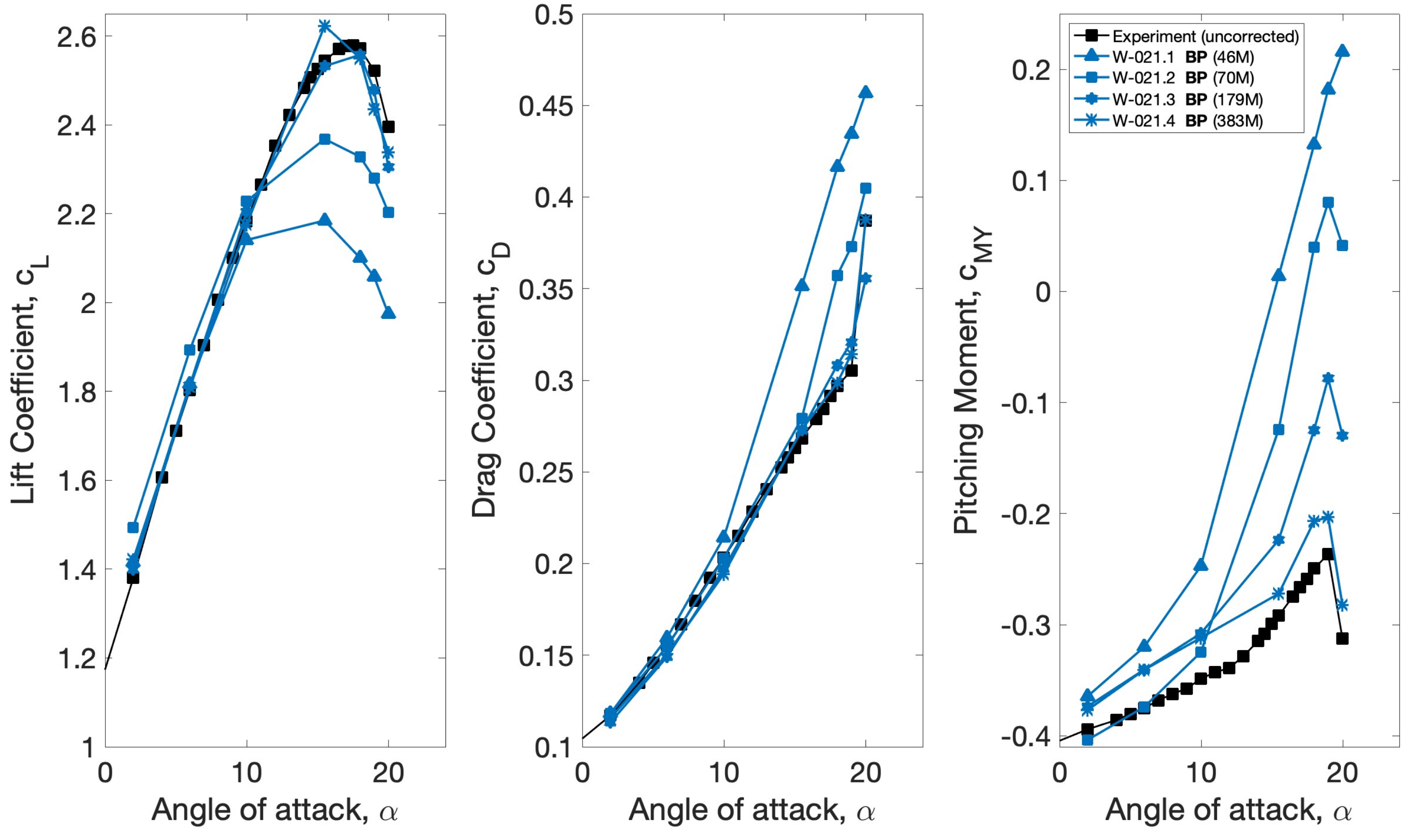
Best Practice (BP) Only – Wind Tunnel (case2b)

All three submitted results predict CLmax within 2% accuracy and observe a strong pitch break

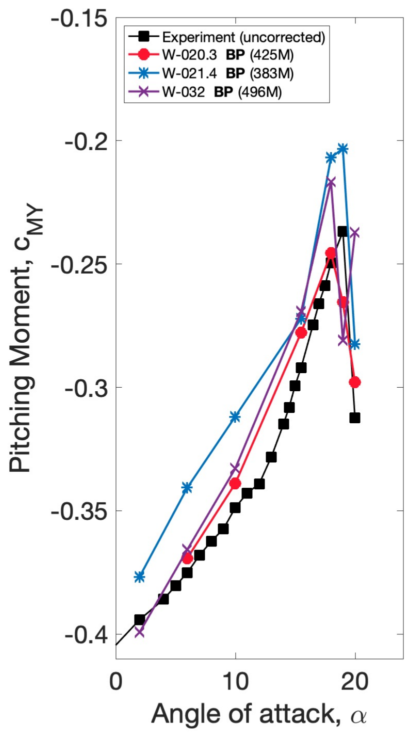


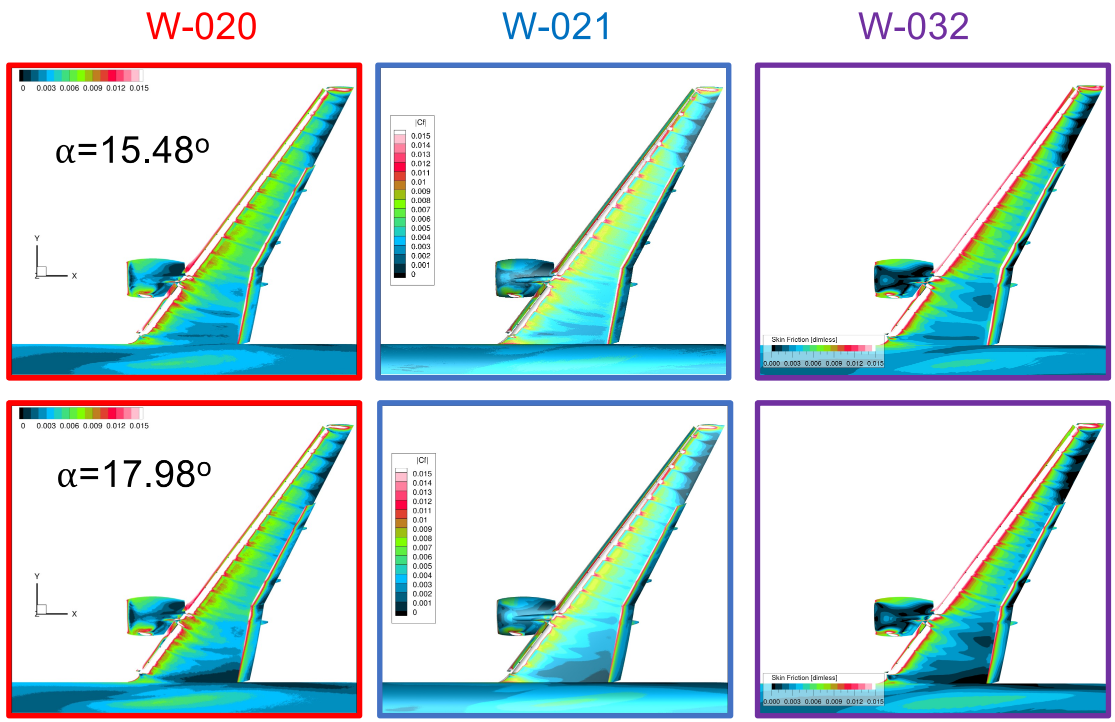
Integrated Loads
Grid Sensitivity W-021

Additional grid level may be needed.



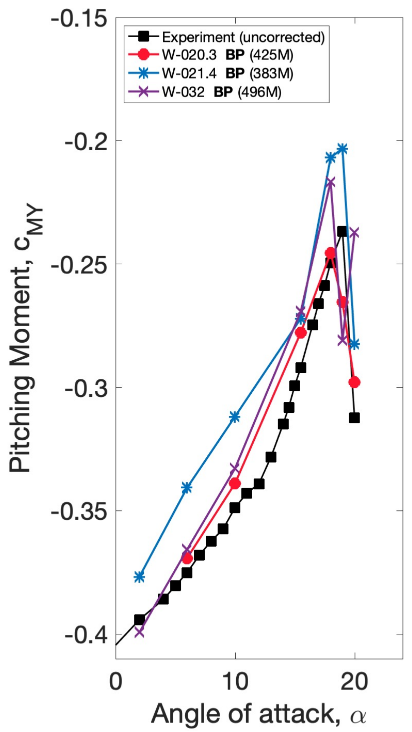
Flow Topology 15.48° to 17.98°

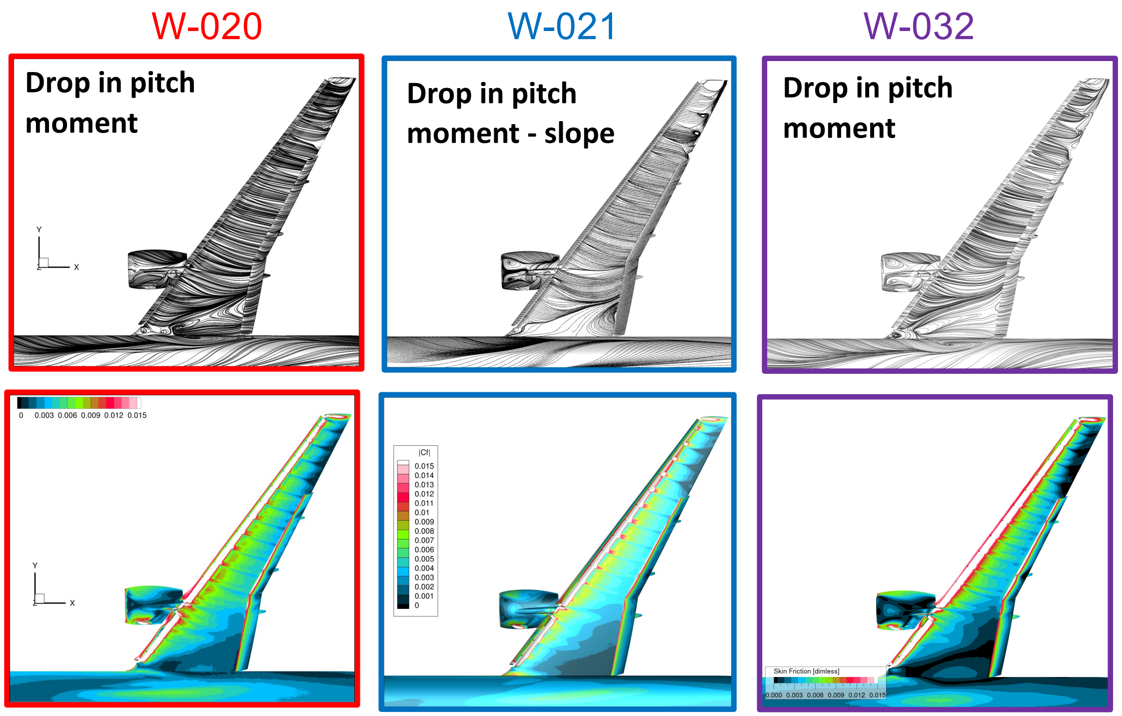




Similar inboard and outboard flow topologies between the three submission.

Flow Topology at 18.97°

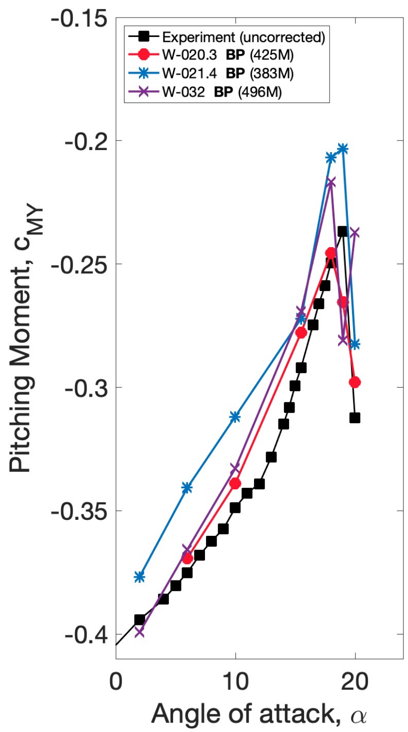


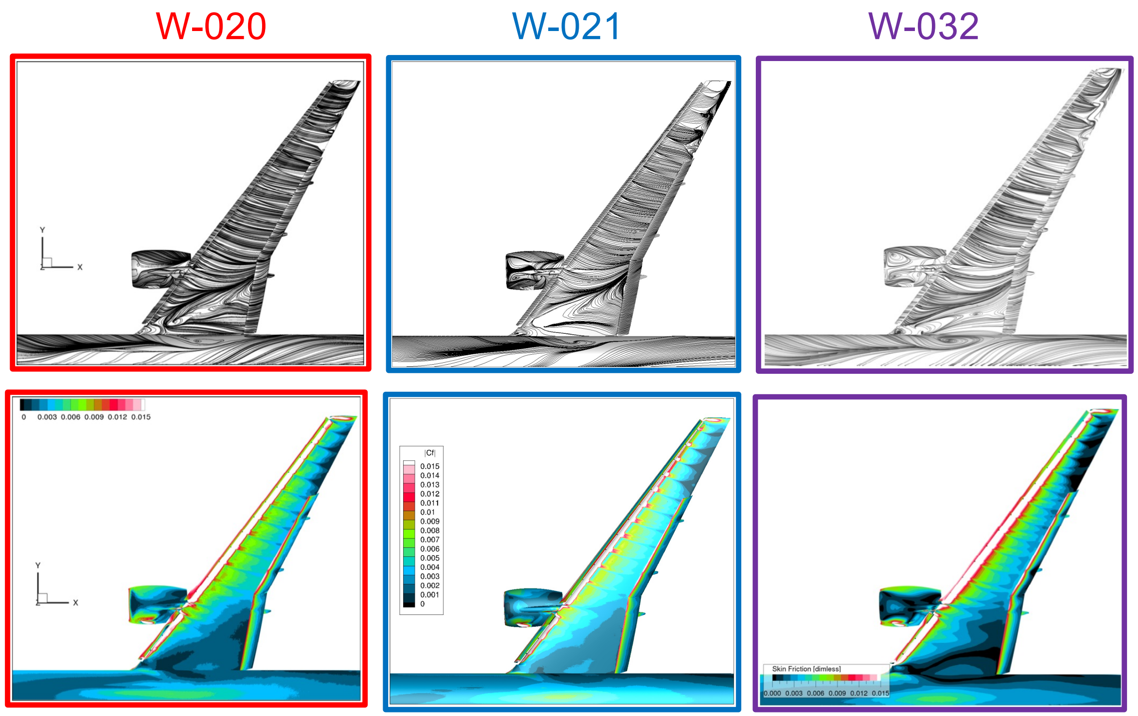


Fully formed corner flow separation reported on all three participants simulations – one degree before experiment stall

Flow Topology at 19.97°

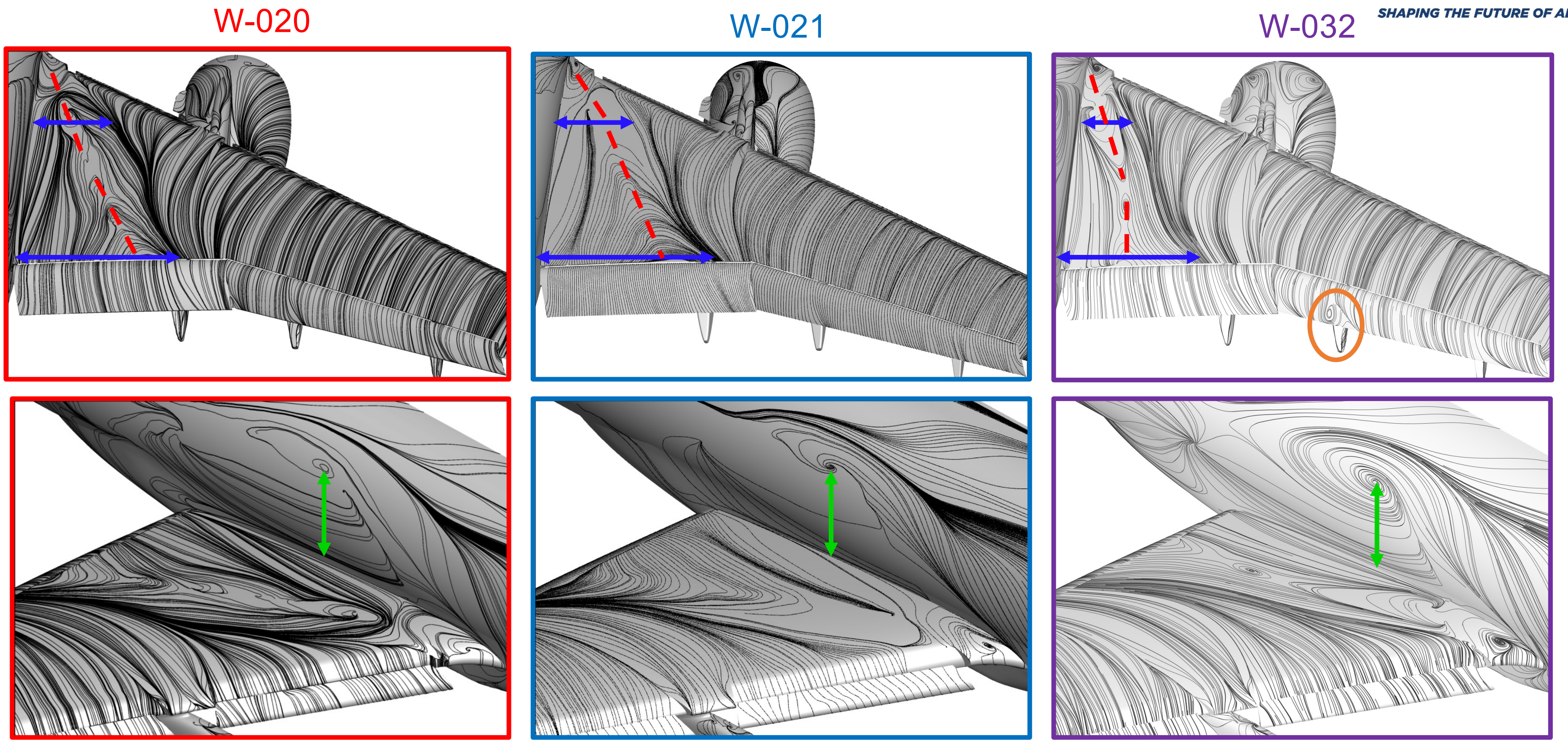
W-020 and W-021 have a virtually identical stalled-state





Surface Streamlines at 19.97° (WT)

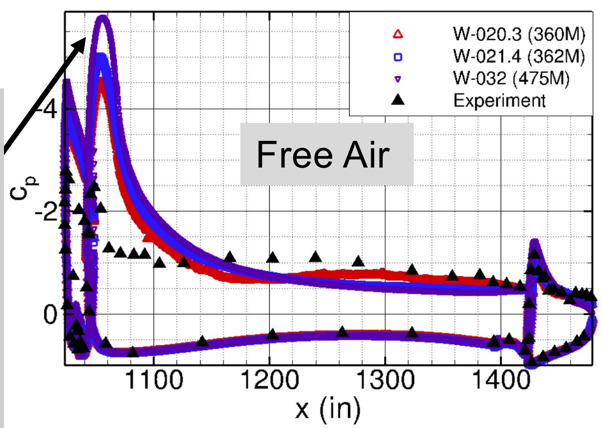
W-020 and W-021 have a virtually identical stalled-state.

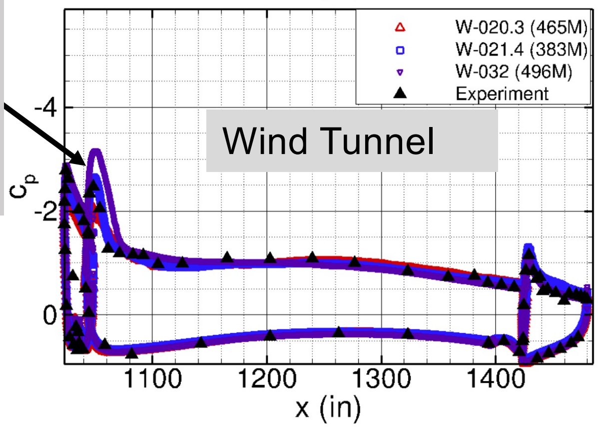


CP slices at 21.47º (FA) and 19.98º (WT)

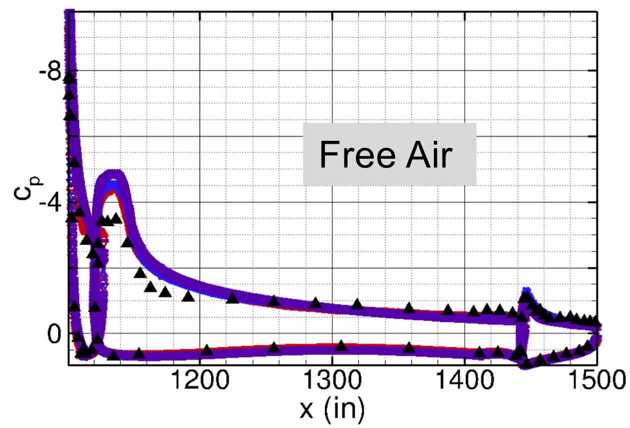
Similar sensitivity between participants at suction peak and sharp drop in the suction peak going from free air and wind tunnel cases at highest angle (21.47º/19.97º)

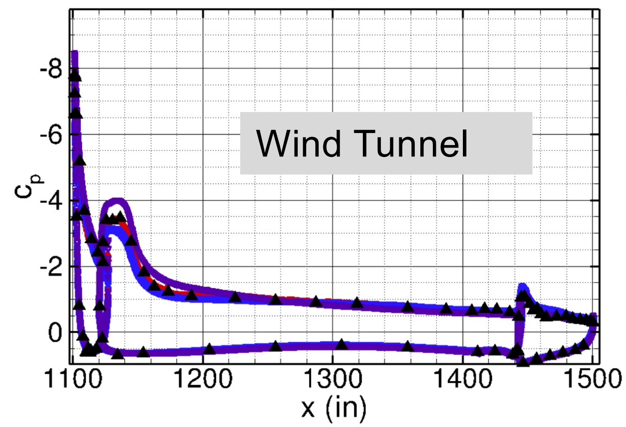
Station A

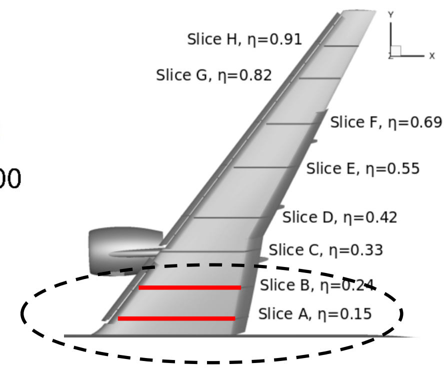




Station B

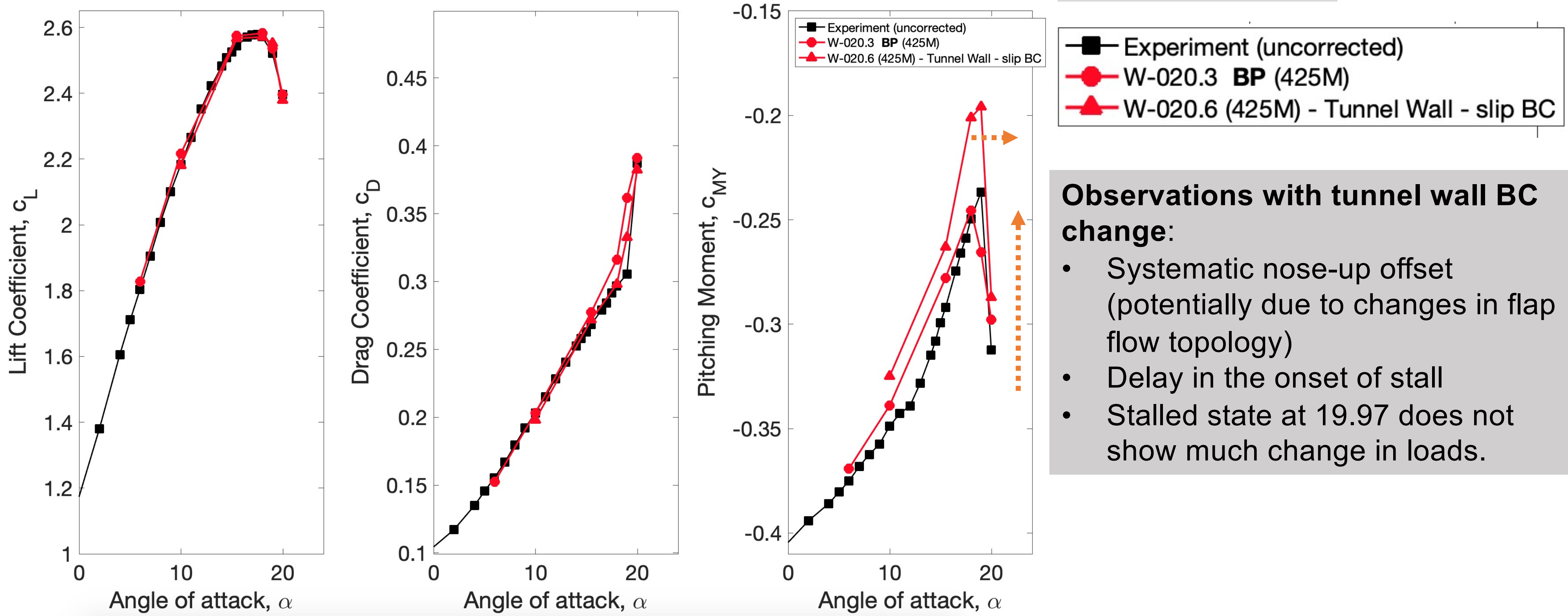






Sensitivity to Tunnel Wall BCs

Group W-020 ran additional simulations using a slip wall boundary condition for the tunnel walls



Observations with tunnel wall BC change:

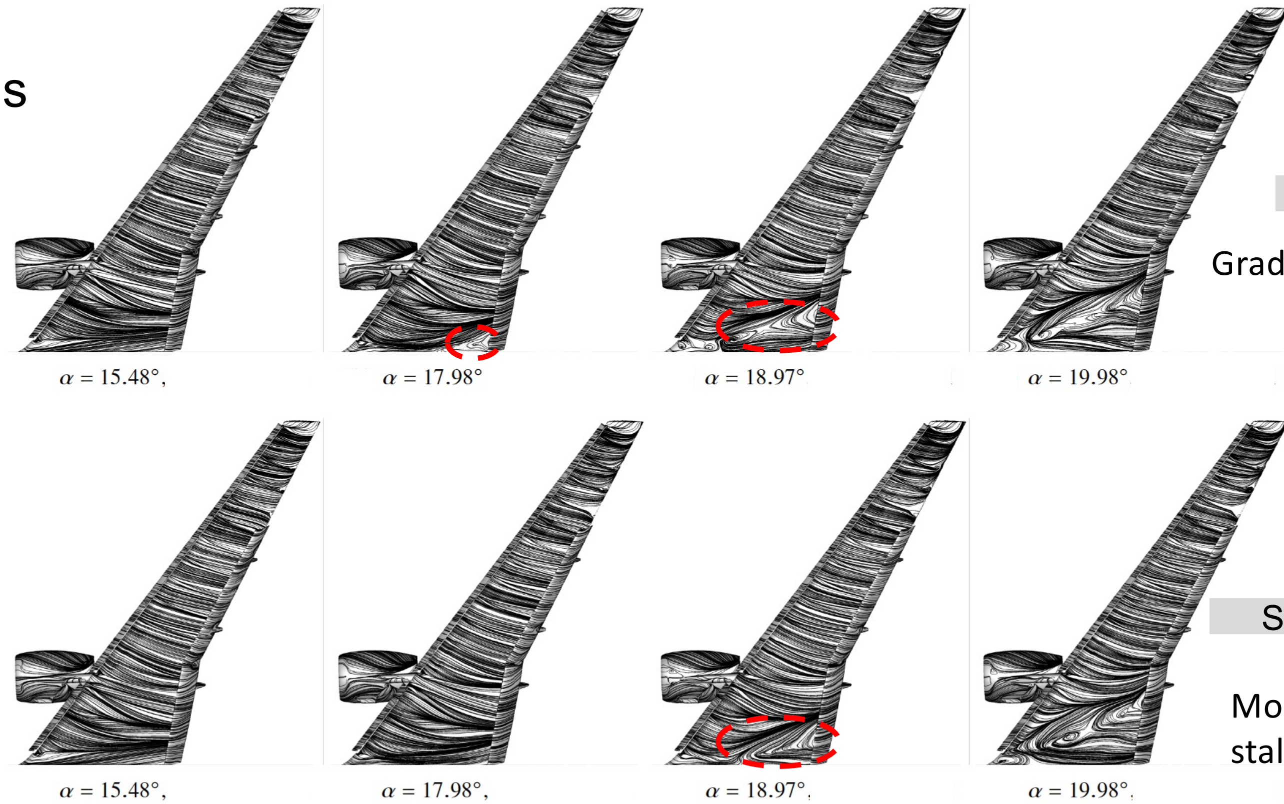
- Systematic nose-up offset (potentially due to changes in flap flow topology)
- Delay in the onset of stall
- Stalled state at 19.97 does not show much change in loads.

Sensitivity to Tunnel Wall Boundary-Layer

SHAPING THE FUTURE OF AEROSPACE

W-020 Submissions

Sensitivity to tunnel wall boundary-layer seen for alpha>17^{o} although strong sensitivity is not observed at highest angle (19.98^{o}).



Viscous WT BC

Gradual inboard stall

Slip wall WT BC

More rapid inboard stall

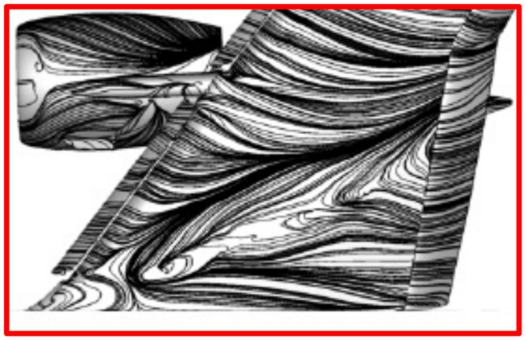
Sensitivity to Tunnel Wall Boundary-Layer

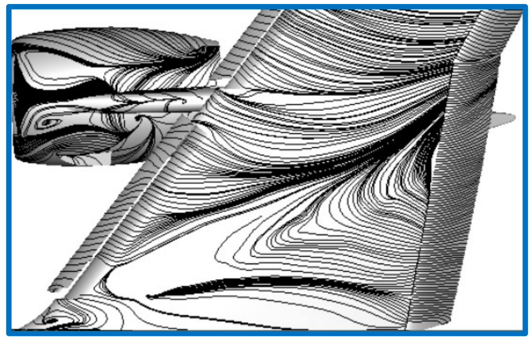
W-020

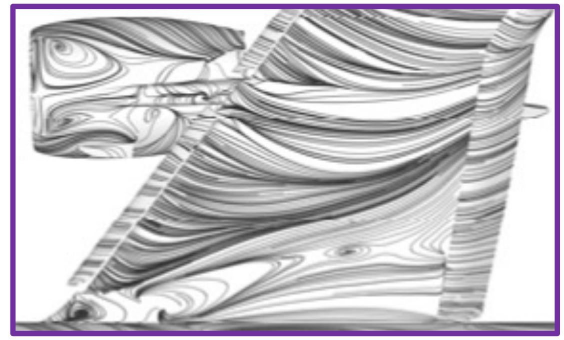
W-021

W-032

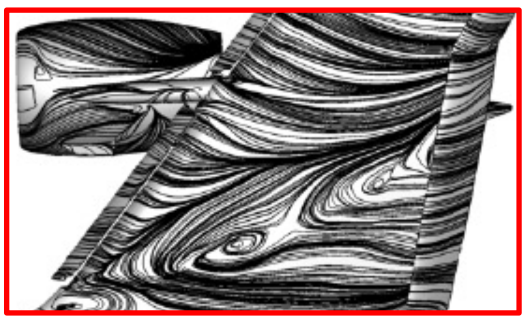
Viscous WT BC





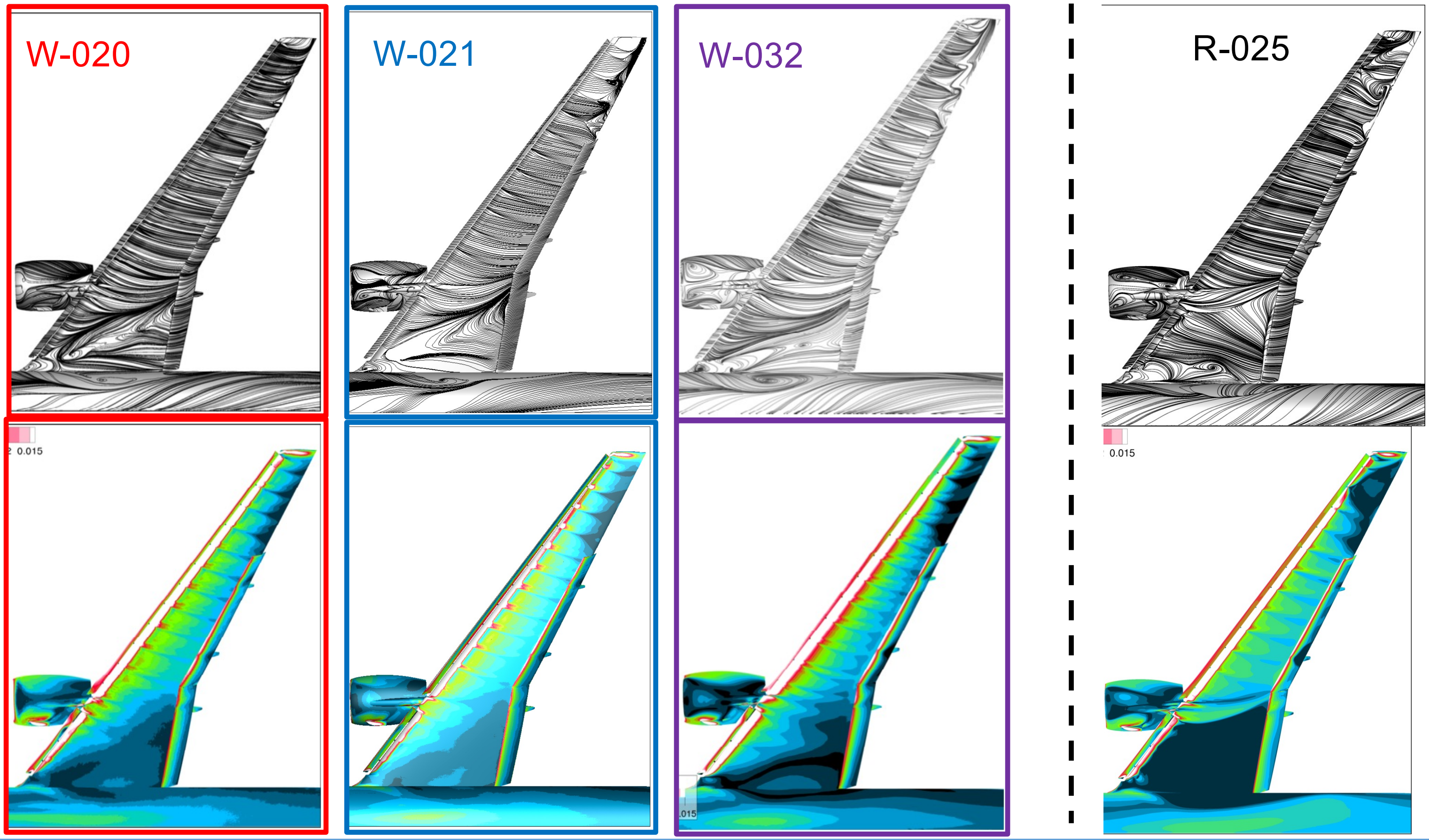


Slip wall WT BC



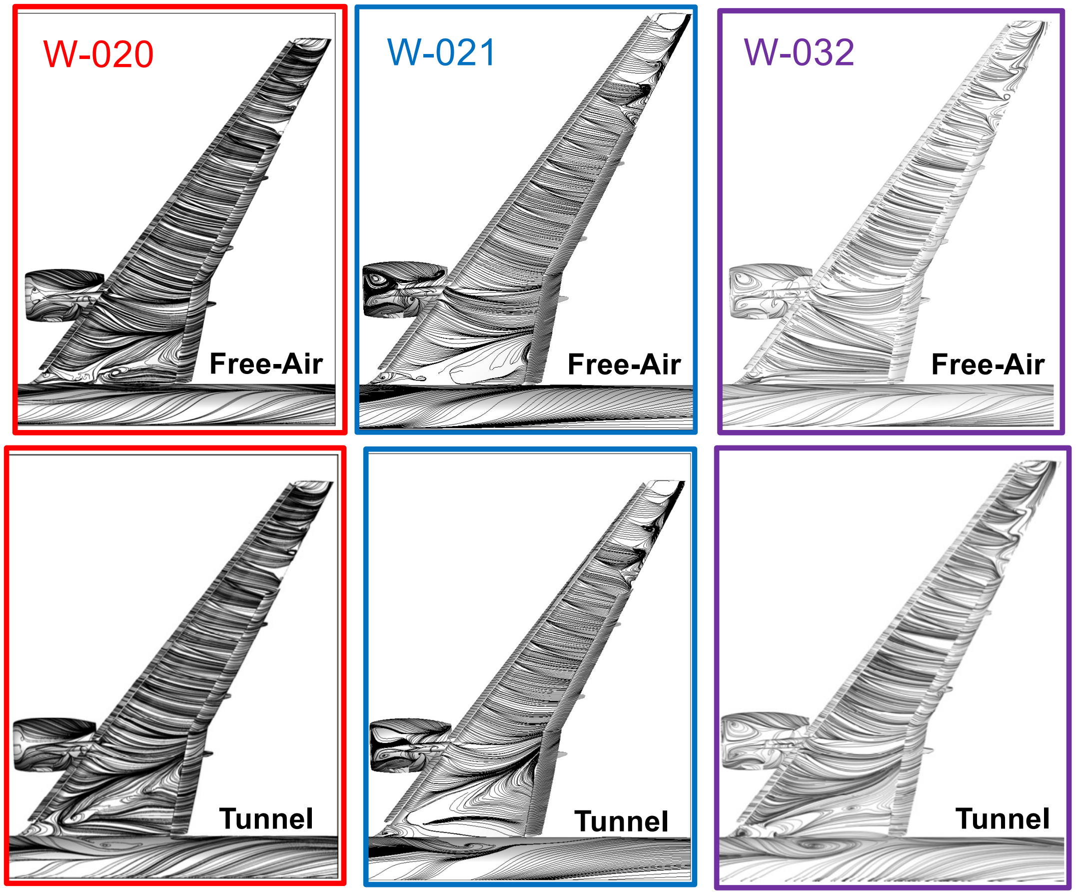
Very similar inboard separation pattern observed at the stalled-state (α=19.98) regardless of the tunnel wall BCs utilized.

WMLES vs RANS: Accuracy

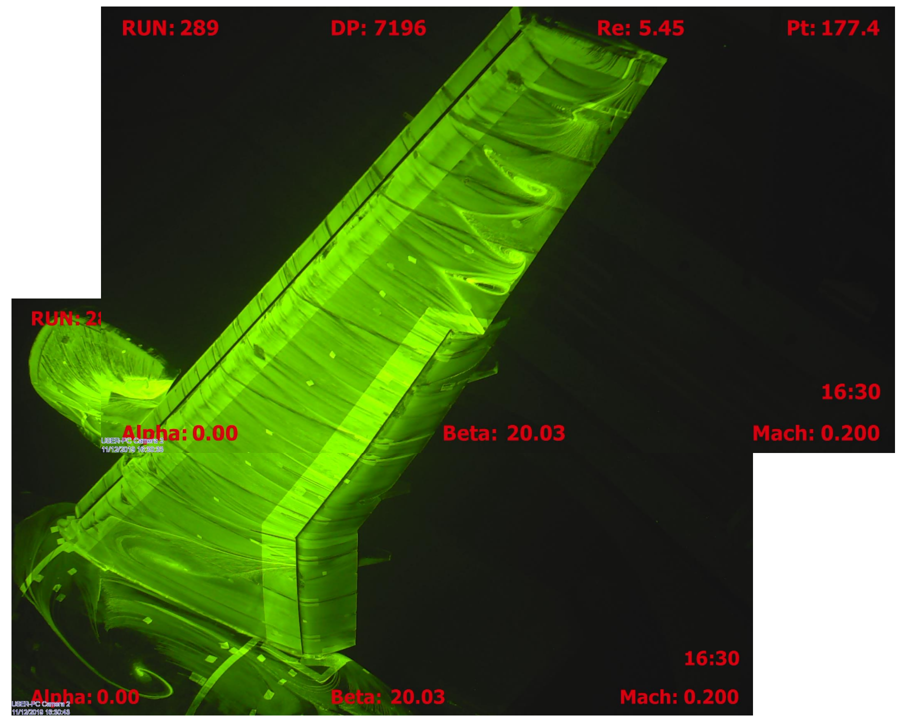


WT simulations at 19.98° for WMLES (left) and RANS (right)

WMLES vs WT Oil Flow



α=19.97



Oil Flow from QinetiQ test

Observations – Wind Tunnel

1. W-020, W-021, and W-032 ran the wind tunnel simulations at all AoA's. Notably less scatter between the WMLES in-tunnel results was observed when compared to the free air case. Their results predicting the aerodynamic loads compared favorably with respect to RANS simulations.

2. W-020 and W-021 reported essentially identical differences to flow-topology going from the free-air to the in-tunnel configuration.

3. These participants went through their due diligence (identifying best practices) in the free air case first and were able to take the lessons learned to the wind tunnel case.

4. Importantly, three LES SGS closures with various grid and discretization strategies predict the correct stall mechanism (loads, moments, cp, surface streamlines) for the correct reasons.

5. While no participants were able to produce a tunnel boundary-layer in agreement with the rake measurements, W-020 and W-021 attempted to assess the sensitivity to tunnel wall boundary layers via conducting additional simulations with inviscid wind tunnel wall-BCs.

6. At post CLmax stall AoA, the surface flow topology appeared to be rather insensitive to treatment of tunnel walls (viscous vs slip BC). This was demonstrated independently by two participants. Moderate sensitivity to tunnel wall BC's was observed in pitching moment at AoA's before the stall.

On the Questions of Thin Leading Edge BLs

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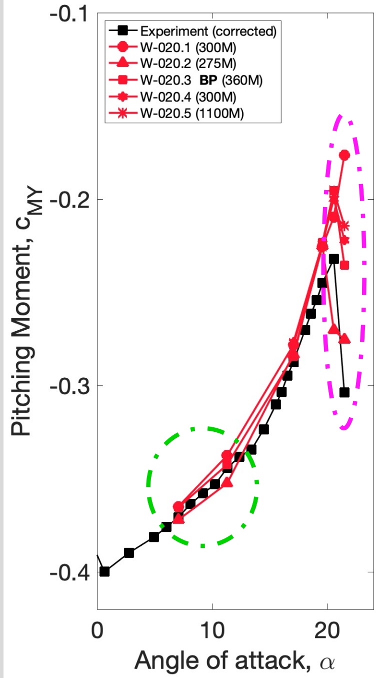
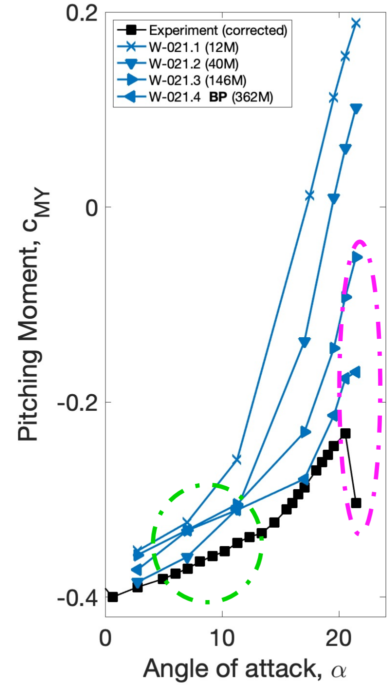
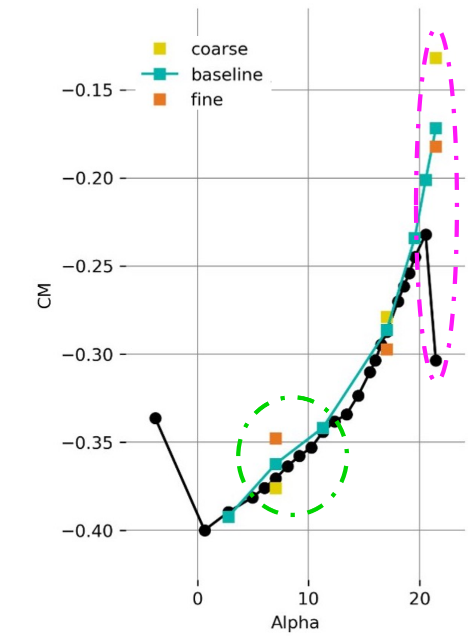
- Not much analysis conducted on the low angles of attack (α<11) to keep the scope more focused on CLmax but it is clear that the flow on the flaps poses some major challenges.
- Sensitivity to pitching moment at both lowest and high angles is potentially associated with low Reynolds numbers i.e. low values of $\delta_{BL}/c(y)$, especially on the **flap** (affects low angles of attack) and the **outboard wing** (affects high angles of attack).
- For more rigorous analysis, the following is needed:
    - Boundary-layer measurements from experimentalists,
    - Information regarding laminar-turbulent transition (e.g. infrared imaging)







On the Questions of Implicit Time-Stepping

For M=0.2 flow:

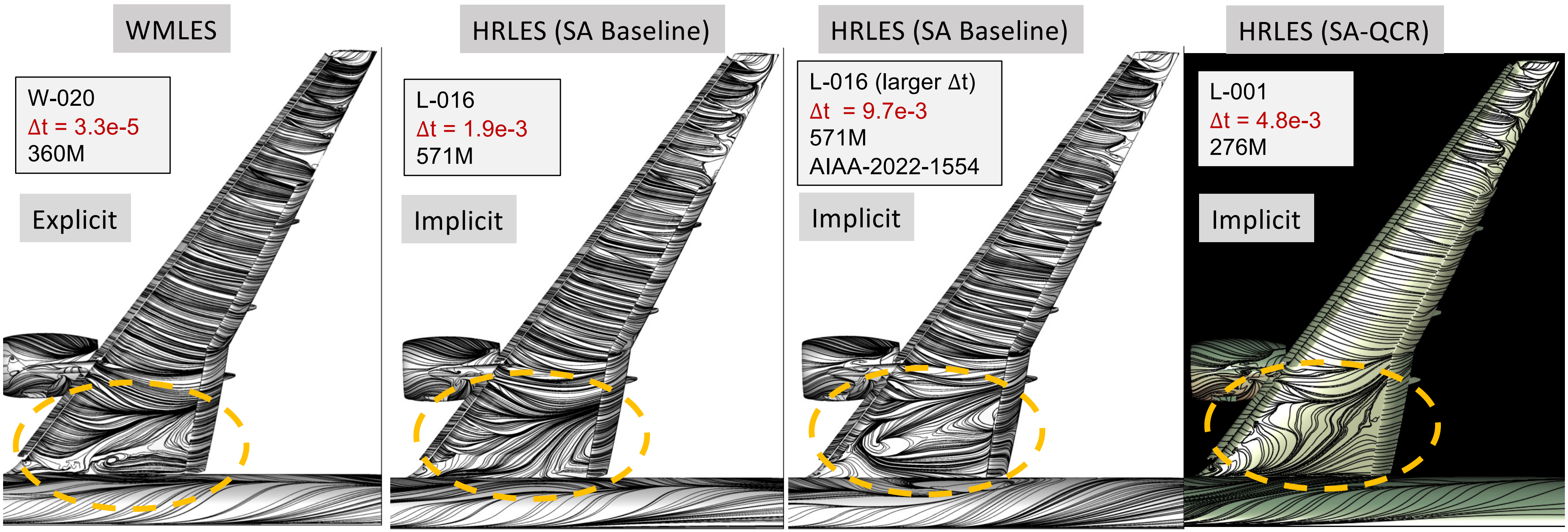
- Differences of timestep between incompressible CFL and compressible CFL are approximately a factor of 5 to 10 – hard to justify use of implicit time stepping for efficiency!
- Most participants who used implicit time-stepping did not have tight control over their grid quality. Therefore, need to employ implicit time-stepping for robustness.
- If it is important to resolve **thin laminar** (as opposed to thin turbulent) boundary-layers, then implicit time may be required.

Group ID	Grid Topology	Time Integration	Justification for Time Integration Scheme
W-020	Structured overset	Explicit (Compressible NS)	Efficiency
W-021	Voronoi unstructured	Explicit (Compressible NS)	Efficiency
W-032	Cartesian	Explicit (non-isothermal LBM)	Efficiency
W-049	Cartesian	Explicit (Compressible NS)	Efficiency
W-034	Unstructured	Explicit conv/nonlinear + implicit viscous/linear (incompressible NS)	Efficiency (implicit operator is linear)
W-030	Unstructured adaptive mesh	Implicit (Compressible Euler)	Robustness (grid quality)
W-031	Unstructured	Implicit (Compressible NS)	Robustness (grid quality)
W-047	Unstructured	Implicit (Compressible NS)	Robustness (grid quality)
W-050	Unstructured	Implicit (Compressible NS)	Robustness (grid quality)

- Some participants have suggested that utilization of substantially larger time steps (for implicit schemes) to optimize cost vs accuracy - although no evidence has been submitted.

On the Questions of Implicit Time-Stepping

Δt: non-dimensional time step



- Some participants have suggested that utilization of substantially larger time steps (for implicit schemes) to optimize cost vs accuracy - although no evidence has been submitted.

Computational Cost

WMLES cost estimates relative to a steady state RANS simulation

NAS Node Type	NAS SBU Rate
AMD Rome	4.06
CAS GPU (4 V100)	9.82
SKY GPU (8 V100)	15.55
Skylake	1.61
Broadwell	1.0
ARM A64FX	1.0**

Shaded data represents participants who attempted in tunnel simulations.

These are cost estimates based on information provided by participants.
***average between CAS V100 and SKY GPU nodes at NAS**
**** based on a NAS parallel benchmarks** https://doi.org/10.1109/Cluster48925.2021.00106

PID	DOF	CPUhrs/CTU = wallhrs/CTU*No CPU's	1 CTU walltime	Hardware	Equiv. NAS SBU for 50 CTU LES	Cost Fraction
R-025	550M	44800 hrs for steady state	16 hrs for steady state	100 Broadwells	**1600**	**1**
W-020	360M	5510 CPU-hrs	0.43 hrs/CTU	100 AMD Rome Nodes, 12800 cores	**8729**	**5.45x**
W-021	362M	(0.15hrs/CTU)*(96 V100 GPU nodes)	4.5hrs/30 CTU's = 0.15hrs/CTU	96 V100 GPU nodes	**9501***	**5.93x**
W-030	3M	10 CPU-hrs	0.5h	Google Collaboratory (20 cores),	**40**	**0.025x**
W-032	475M	70000 total CPU-hrs/65 CTU's = 1050 CPU-hrs	227h/65 CTU's = 3.5 hrs	Skylake 308 cores	**2169**	**1.35x**
W-034	273M	1144000 total walltime, number of CTU's not provided TBD	12.2 days, number of CTU's not provided TBD	Intel Xeon 3456 nodes	**TBD**	**TBD**
W-047	13M	3300 CPU core/CTU & 60 GPU V100hrs/CTU	103hrs/25 CTU's = 4.12 & 50hrs/25 CTU's	800 intel CPU cores & 30 Nvidia V100	**6600***	**4.13x**
W-049	11.2B	6.4e6/5.8 CTU's = 1.1e6 hrs	1.1e6 hrs/184320 cores = 5.97/CTU hrs	Fugaku 184320 cores	**1145000****	**716x**
W-031	296M	NOT AVAILABLE				
W-050	419M	NOT AVAILABLE				

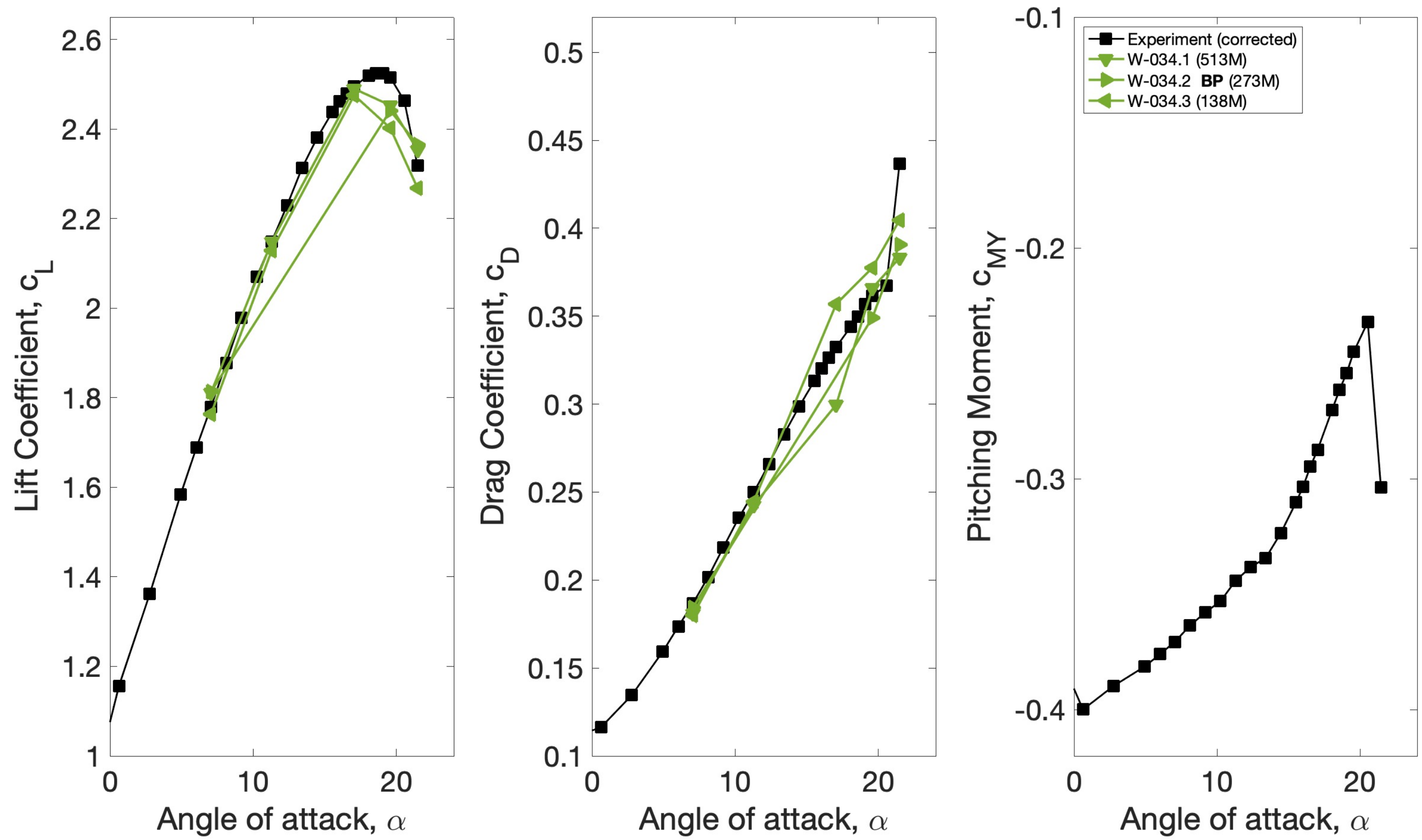
Next Steps

- **What elements of current KQs need further investigation to answer?**
  - Space-time resolution and numerical discretization – additional refinement is needed
  - Optimally targeted refinement - resolving off-body vorticity vs resolving corner flow separation vs resolving thin boundary layers and geometric curvature
  - Relevance of tripping for nacelle separation
- **What additional CFD or test data is required for support the KQs?**
  - Boundary layer data at for tunnel and test article, transition data (thermal imaging), Kulite data (pressure spectra), all at multiple locations.
  - Need temporal data from WT – to quantify any drifts and error bars.
- What additional help is required from the organizing committee to maximize learning?
  - All participants need to submit consistent data
  - Streamline seeding, color maps
  - Need to incentivize frequent active participation – transition from observers to participants

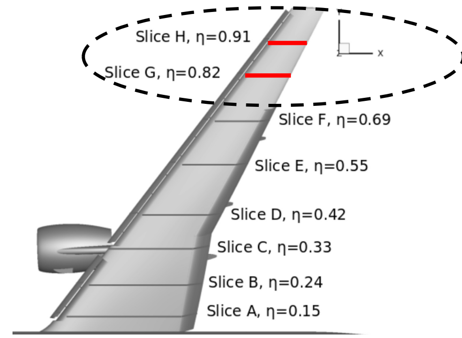
Back-up Charts

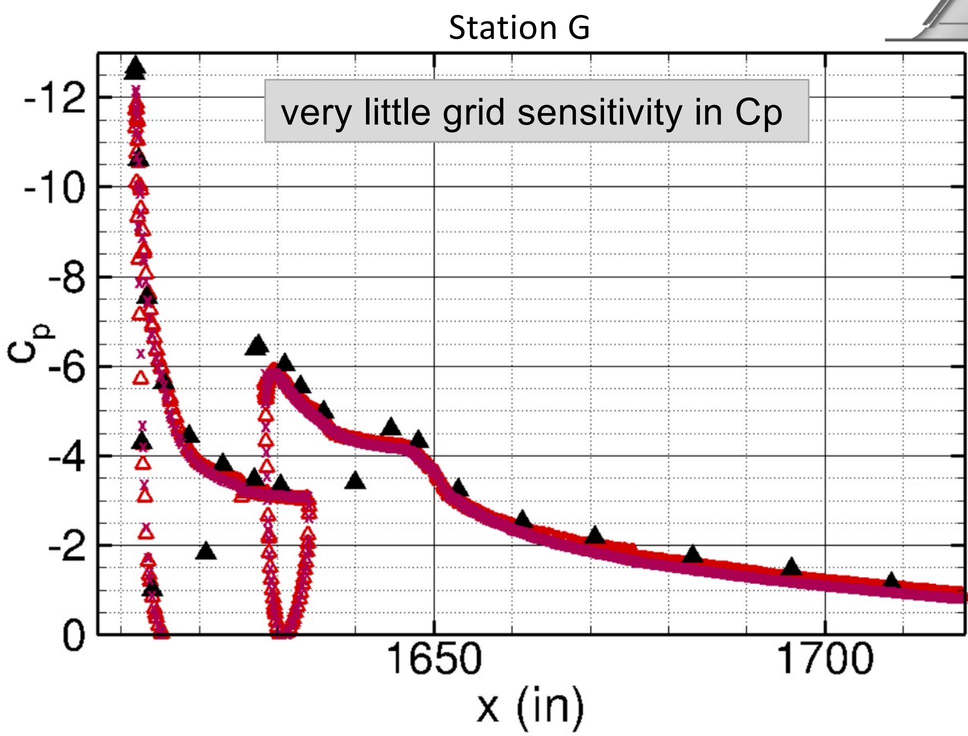
Grid Sensitivity

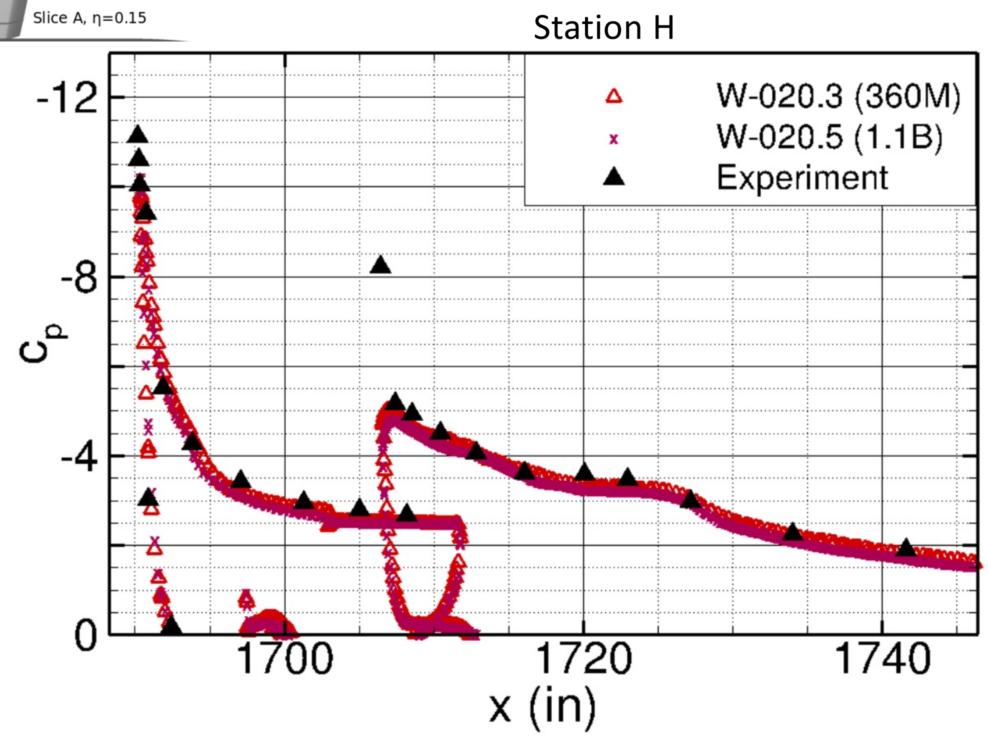
Grid Convergence Studies – Free Air (case2a) – W-034



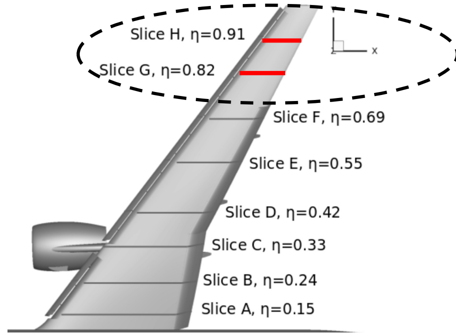
CP slices at 21.47°
Grid Sensitivity – W-020

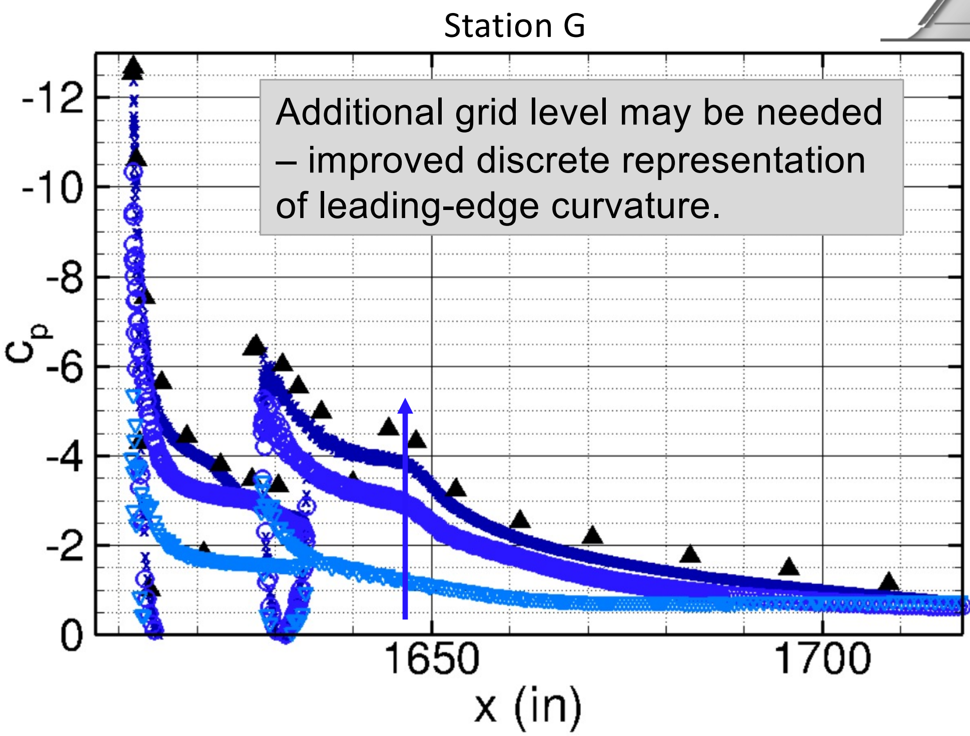


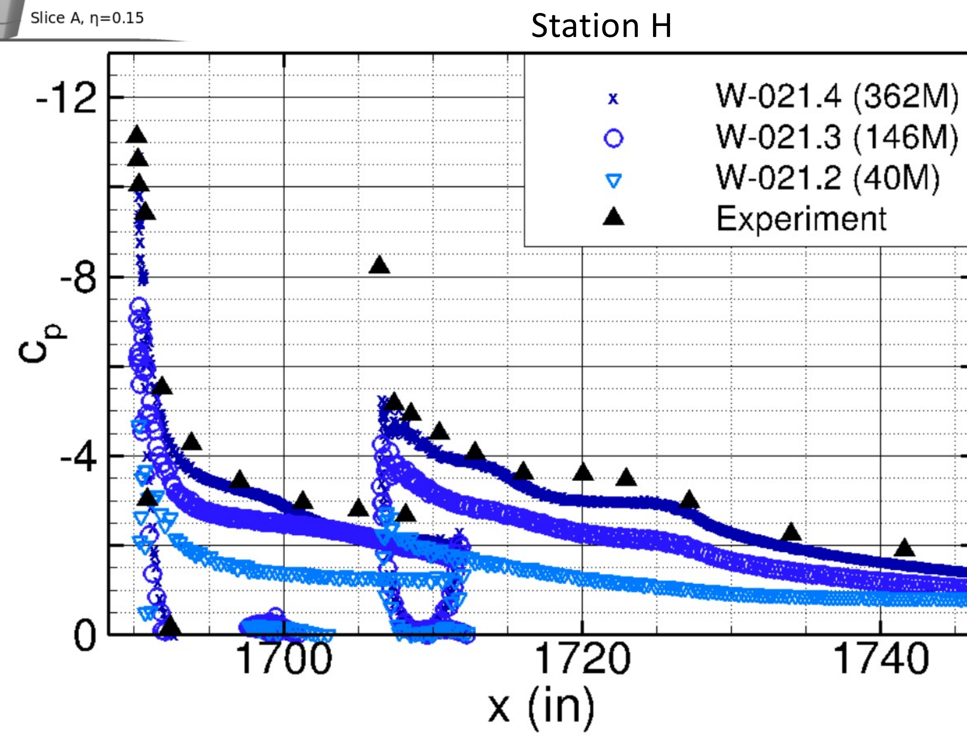




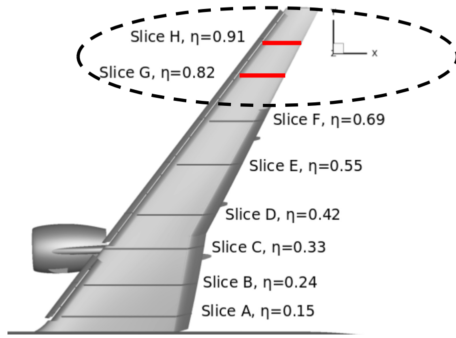
CP slices at 21.47°
Grid Sensitivity – W-021

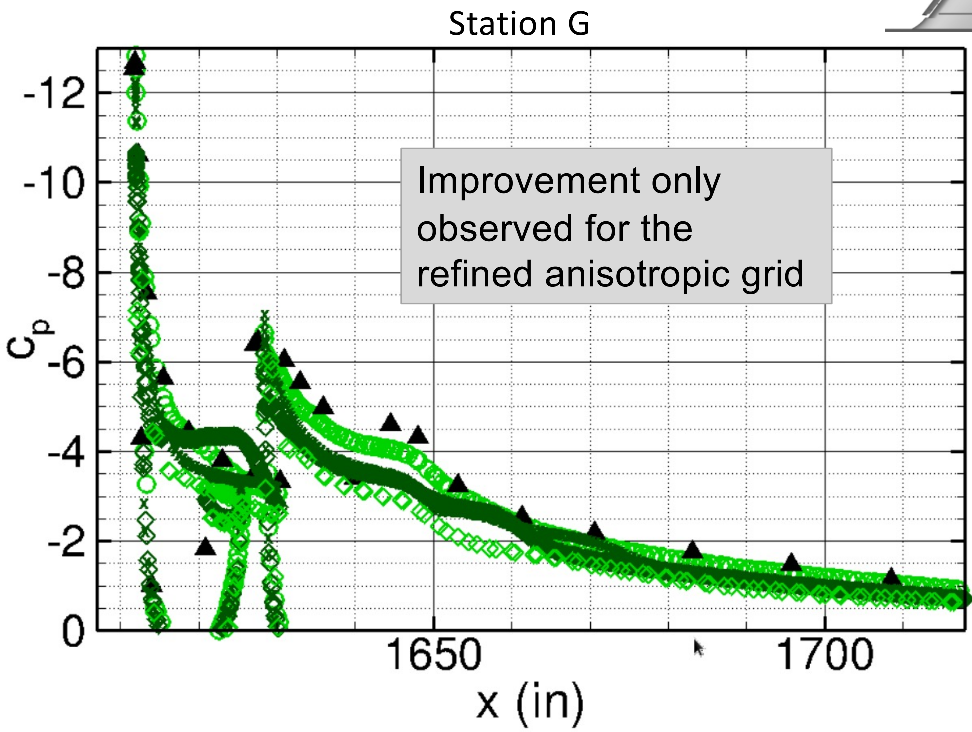


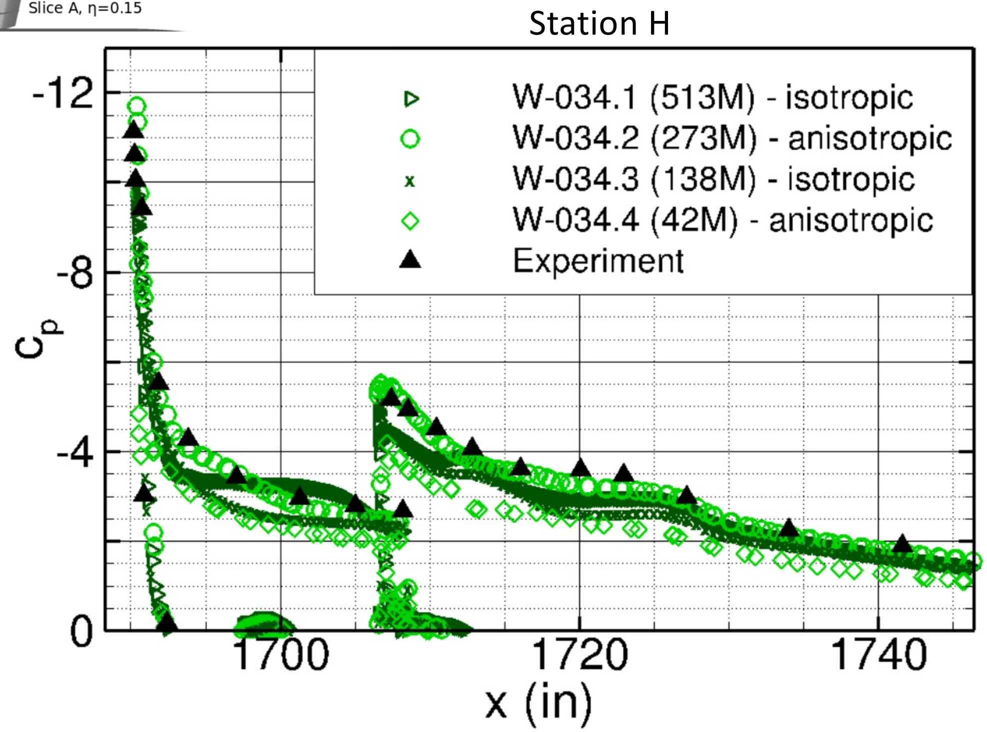




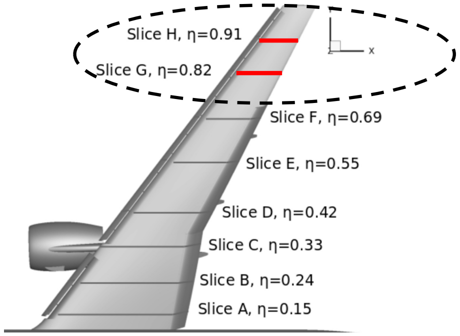
CP slices at 21.47º
Grid Sensitivity - W-034

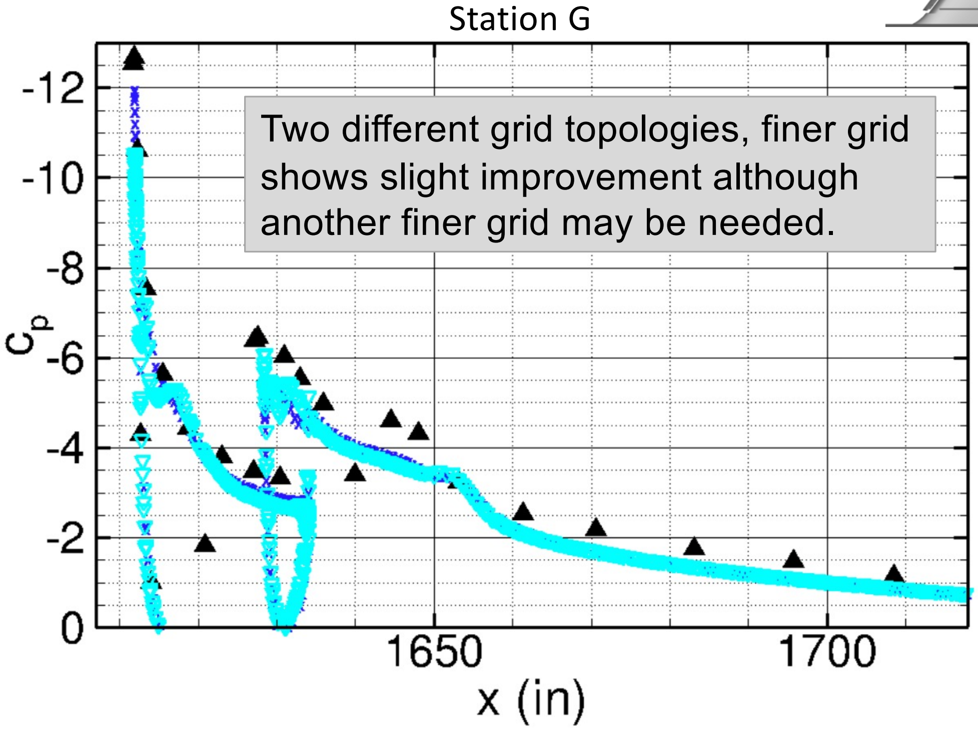


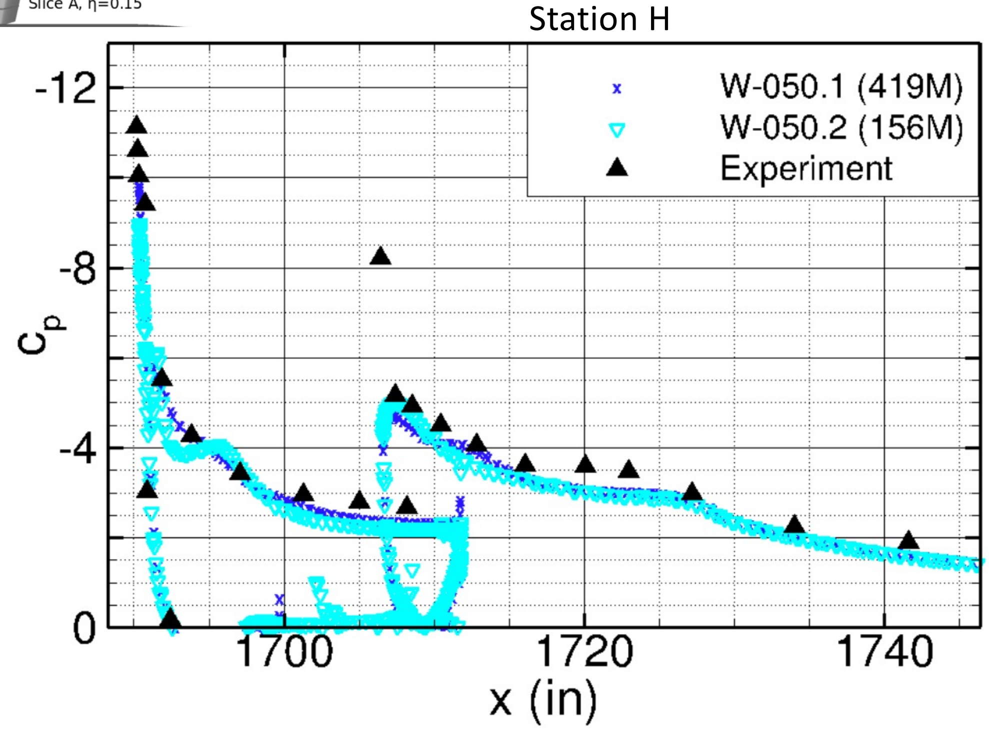




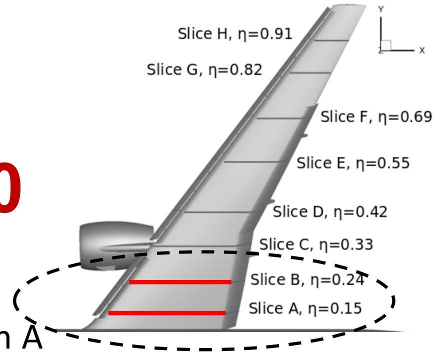
CP slices at 21.47º
Grid Sensitivity – W-050

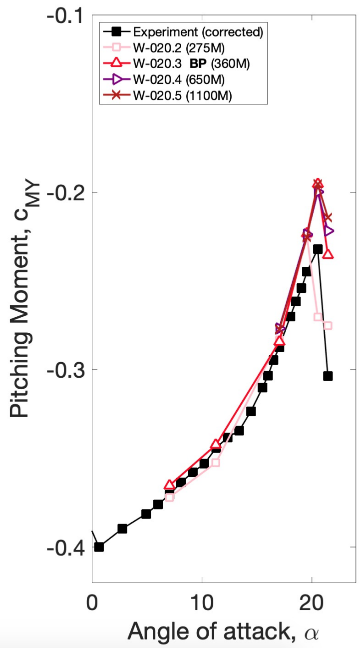




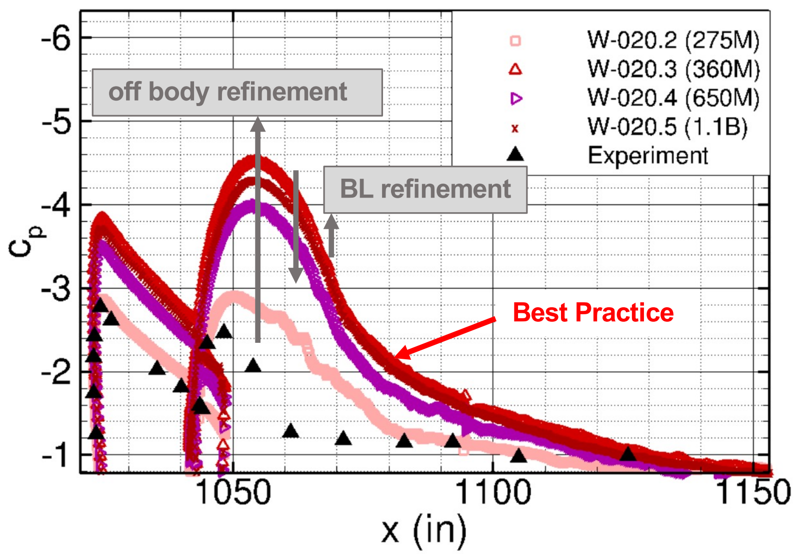


CP slices at 21.47°
Grid Sensitivity – W-020

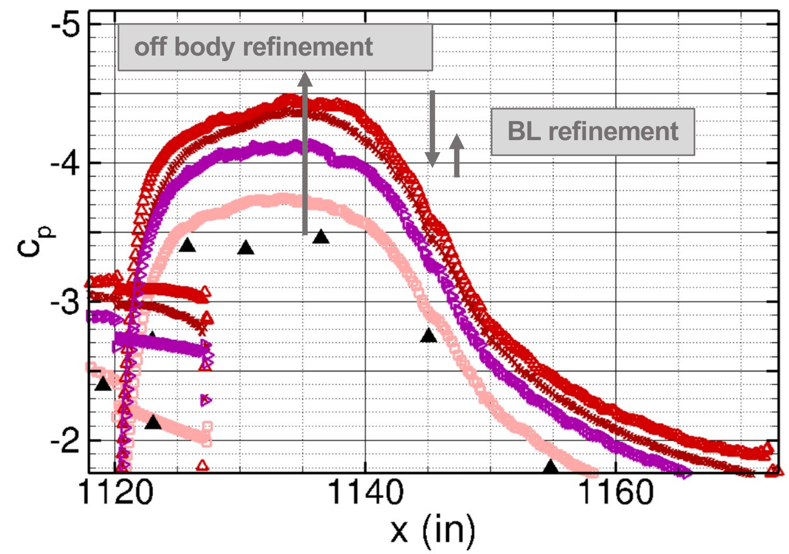




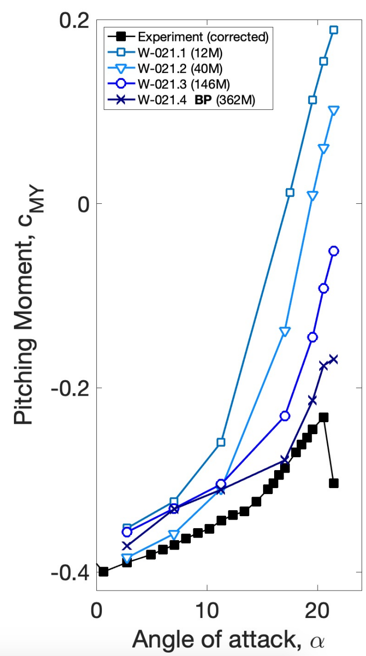
Station A

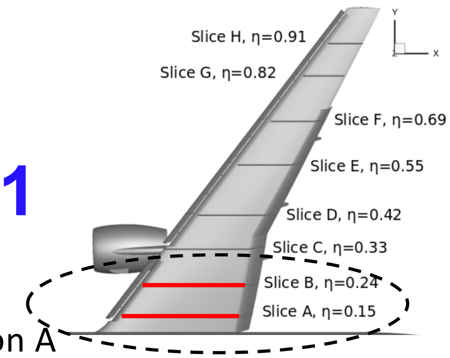


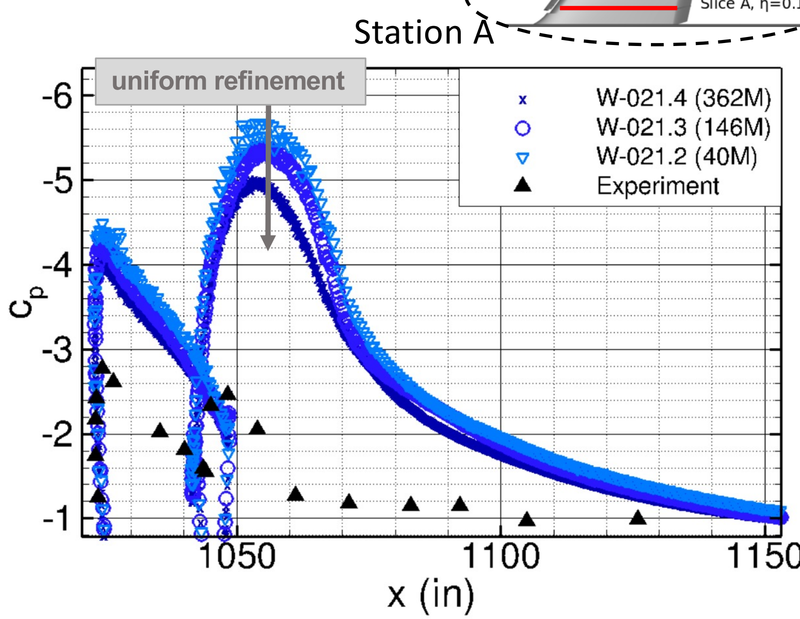
Station B

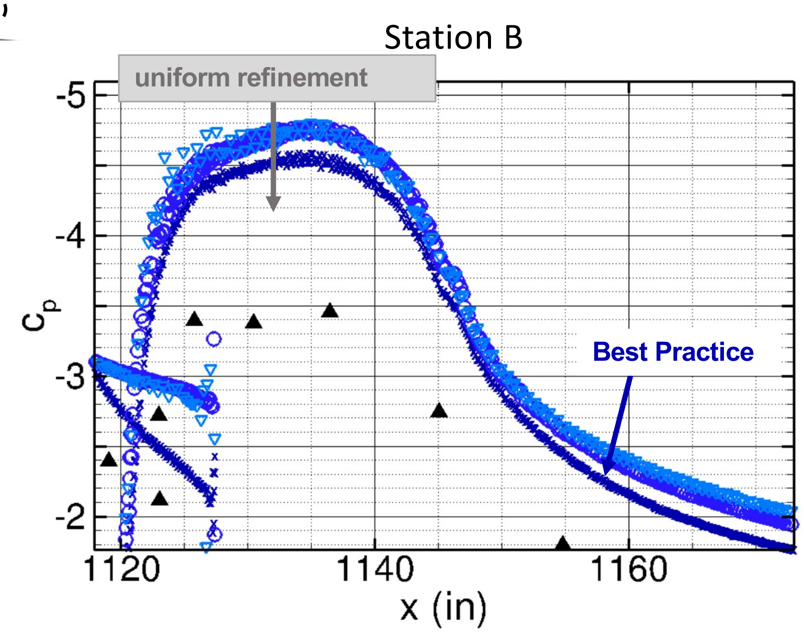


CP slices at 21.47°
Grid Sensitivity – W-021



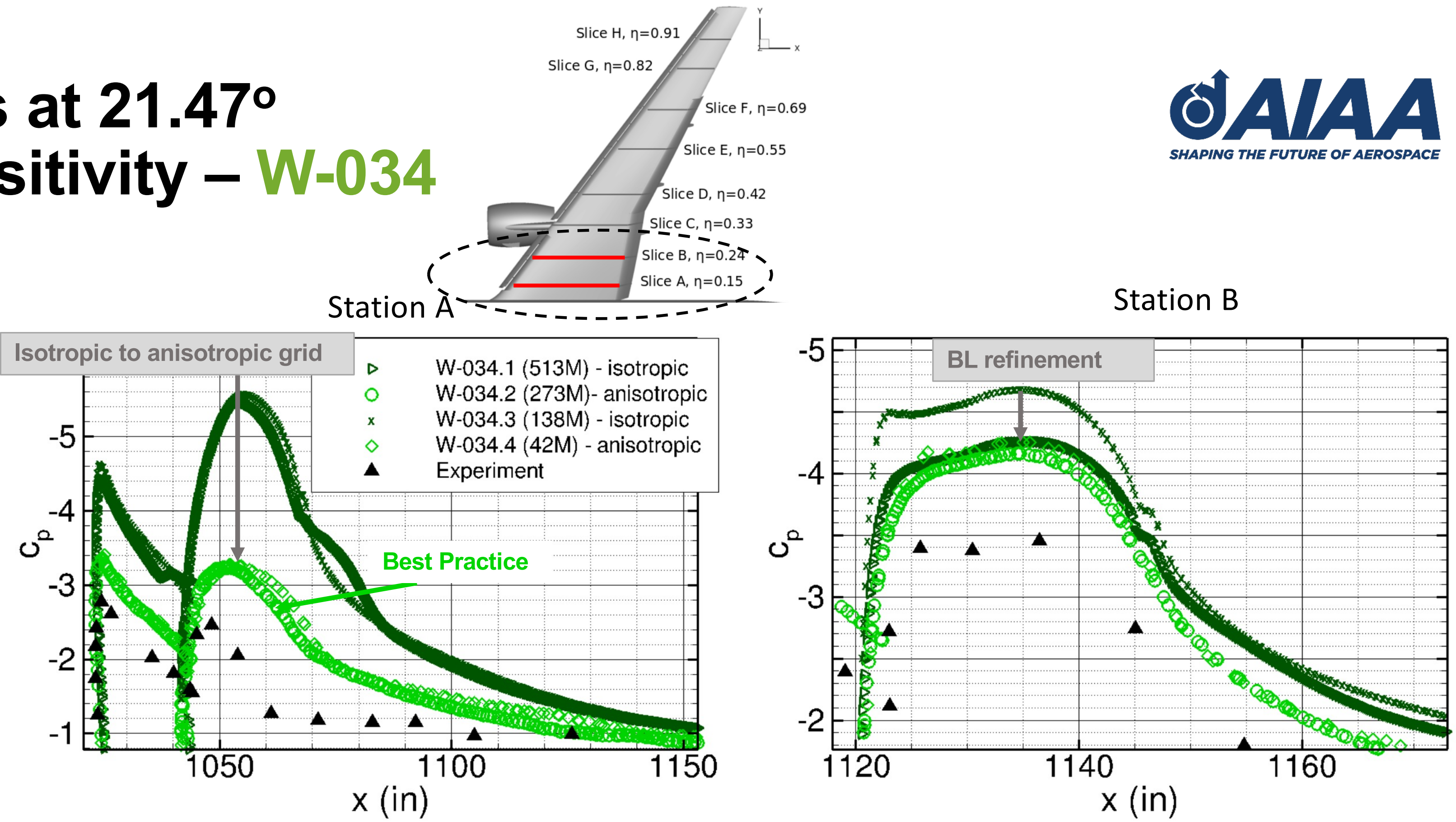




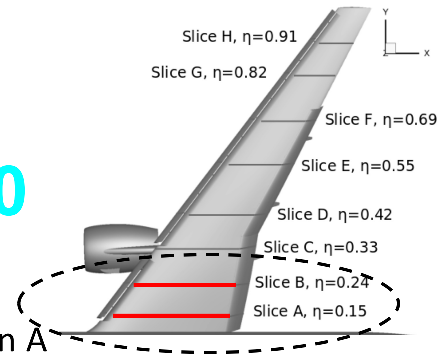


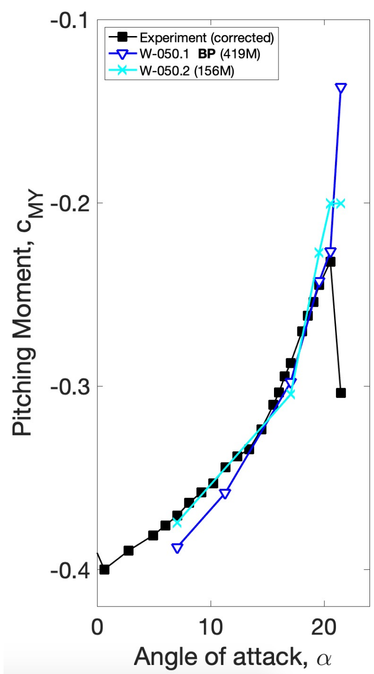
CP slices at 21.47°
Grid Sensitivity – W-034

No pitching moment data provided but cp data is consistent with a large pitch break.

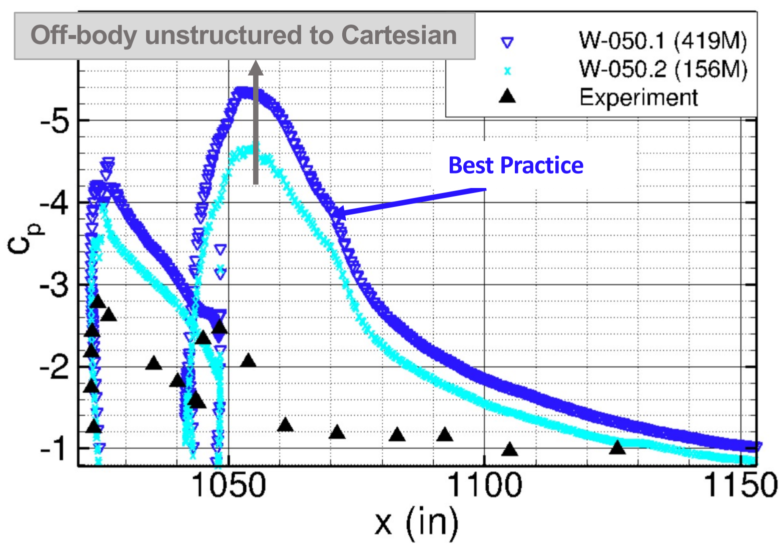


CP slices at 21.47°
Grid Sensitivity – W-050

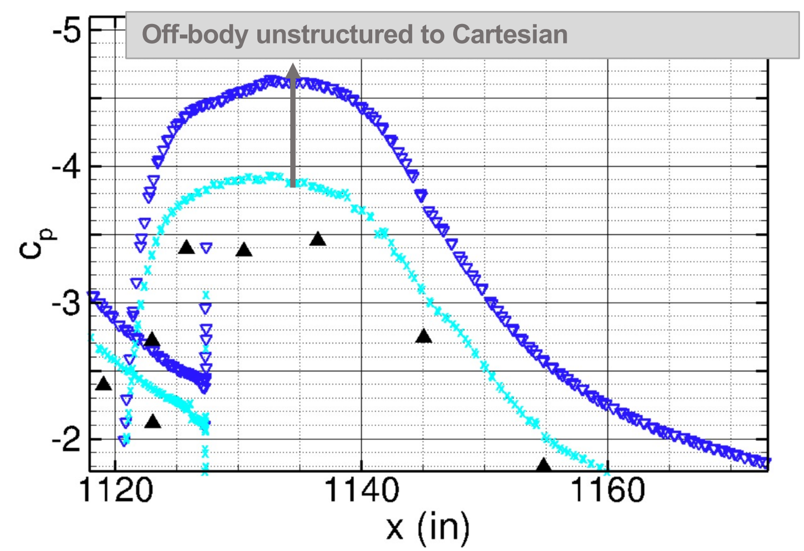




Station A



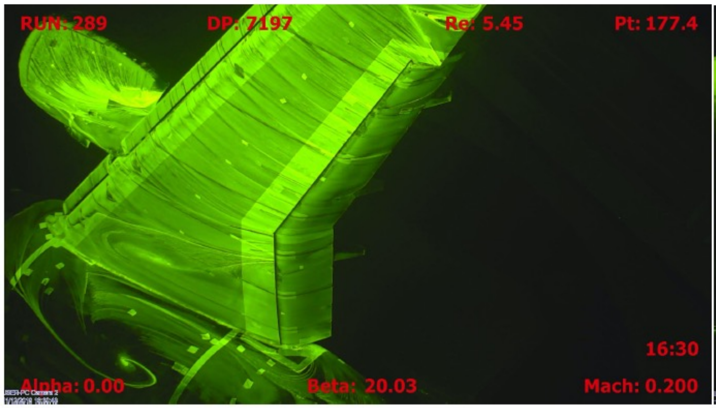
Station B

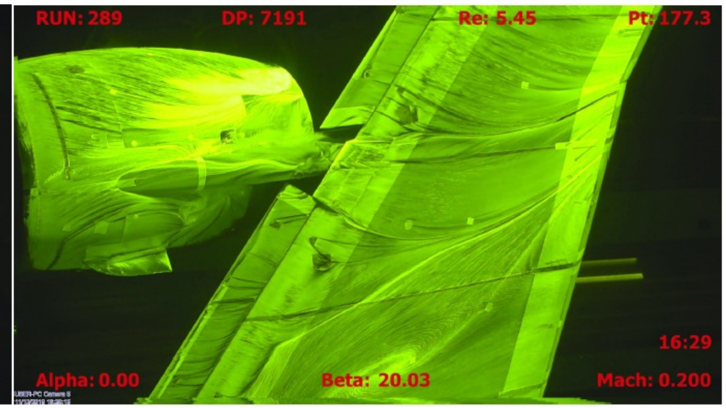


WT WMLES vs RANS: Accuracy

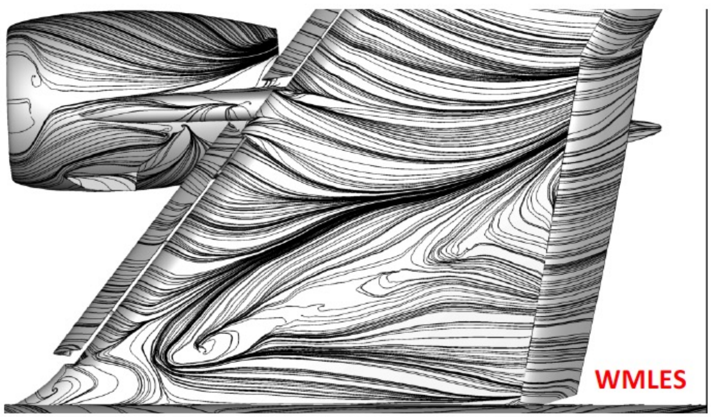
Oil Flow from QinetiQ test

α=19.98





W-020



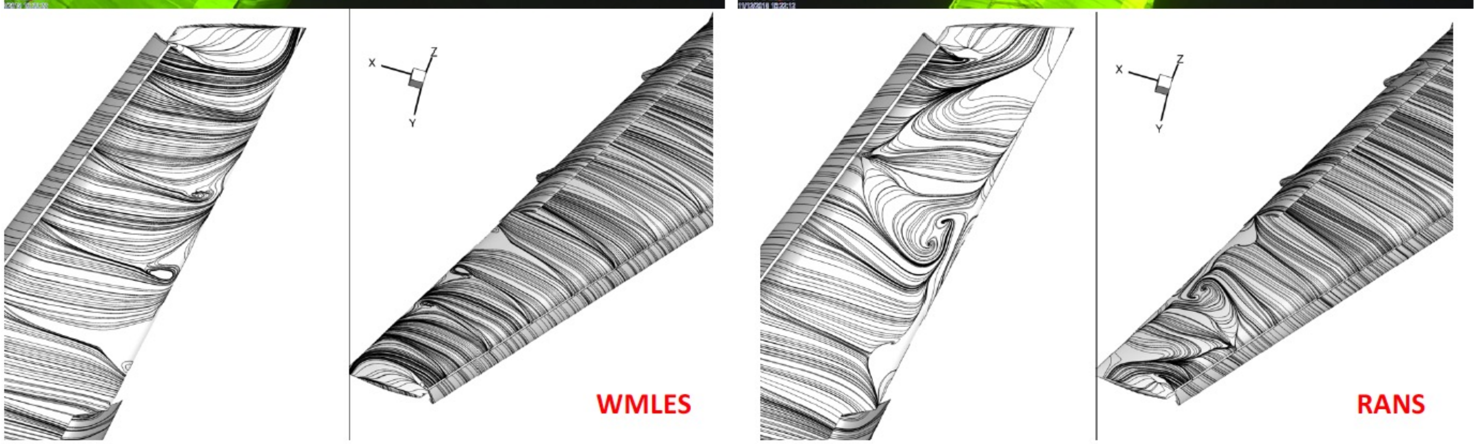
R-025

WMLES vs RANS: Accuracy

Oil Flow from QinetiQ test

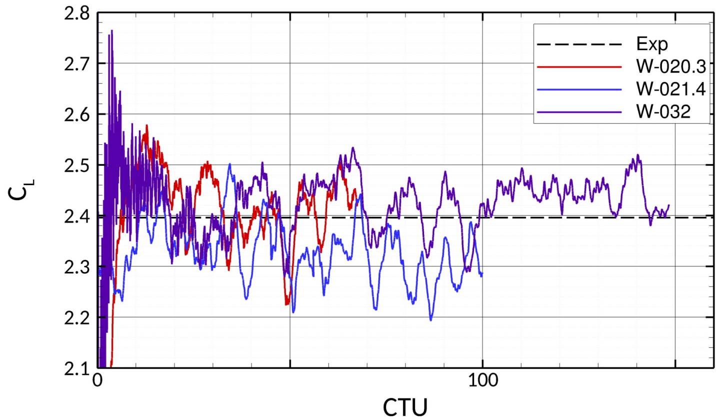
α=19.98

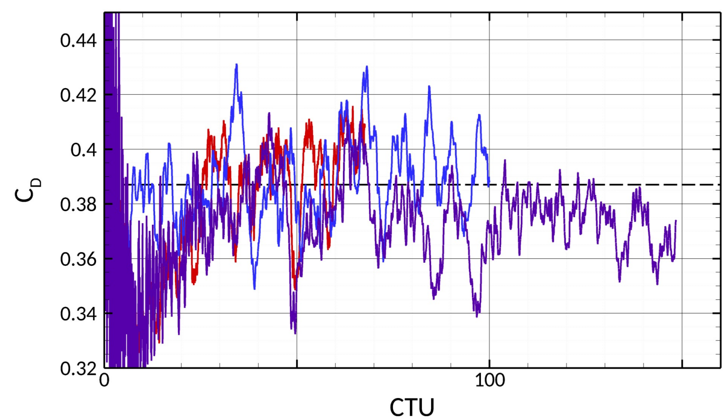
W-020

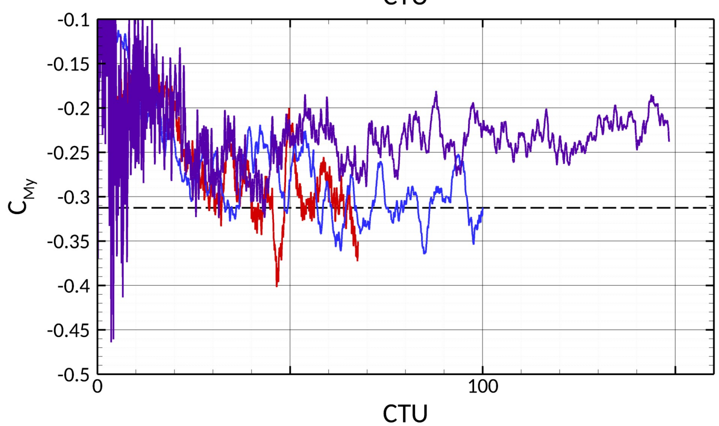


R-025

Aerodynamic Load History at 19.98°



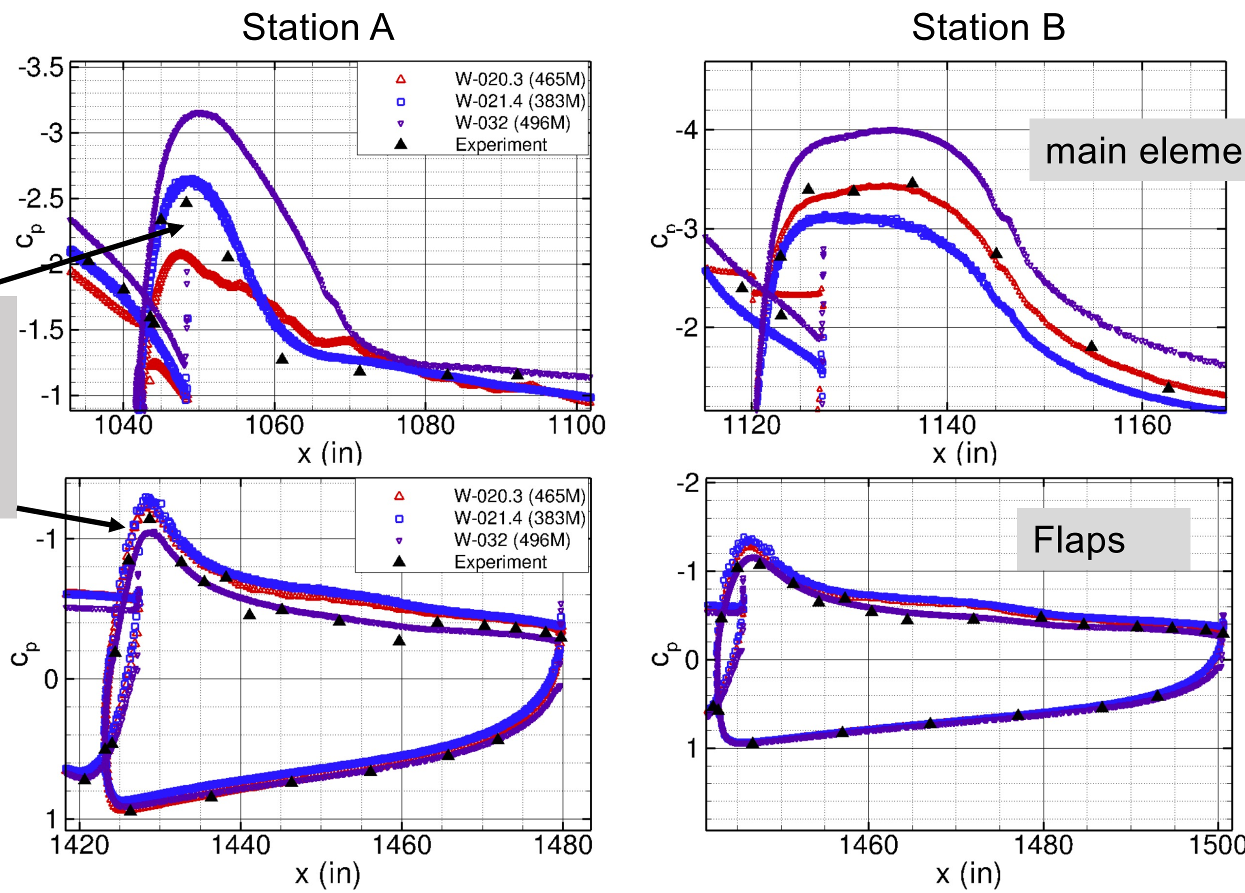




very little sensitivity observed to initial conditions in WMLES/LB

Comparison of CP slices at 19.98° (WT)

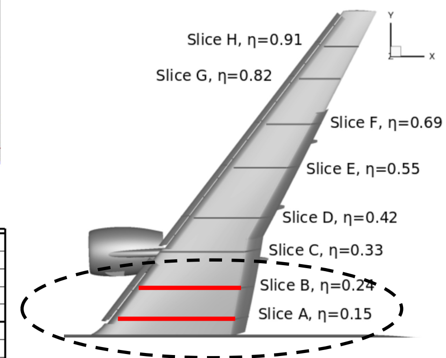
SHAPING THE FUTURE OF AEROSPACE



main element suction peak

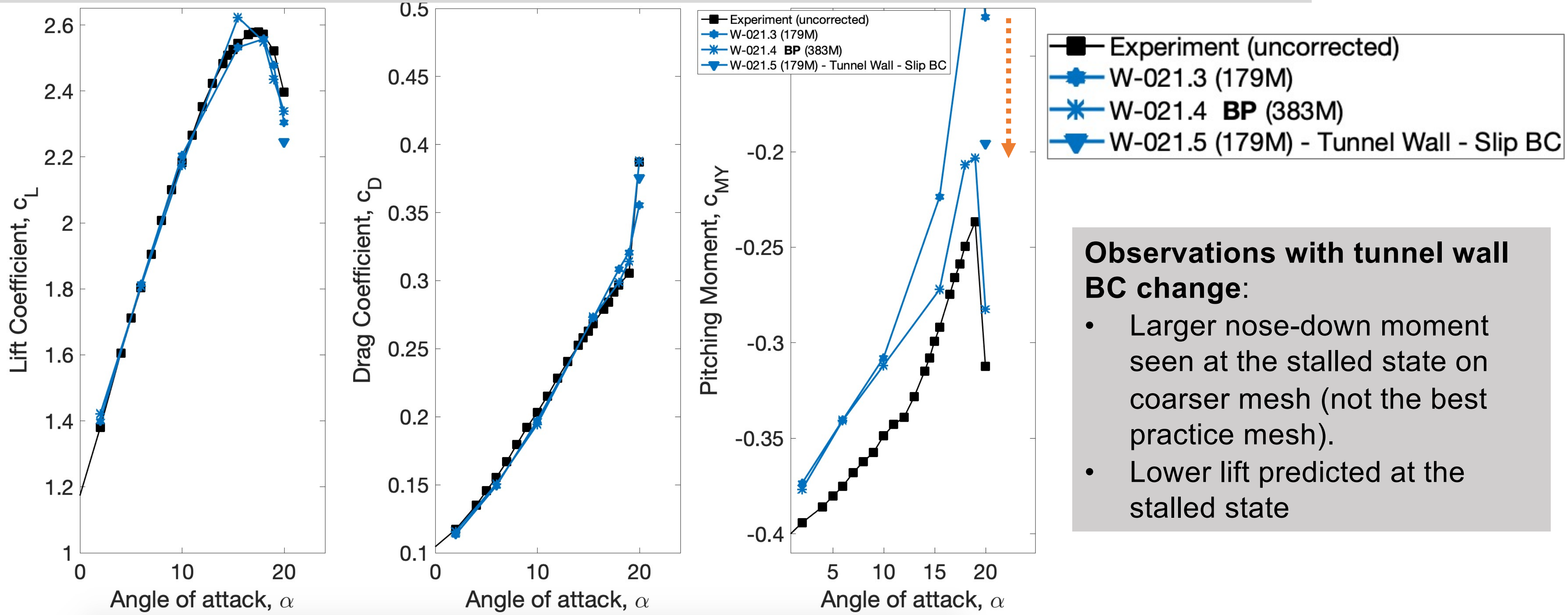
Flaps

CP differences observed at main element suction peak and inboard flaps.



Sensitivity to Tunnel Wall Boundary-Layer

Group W-021 ran additional simulations using a slip wall boundary condition for the tunnel walls



Observations with tunnel wall BC change:

- Larger nose-down moment seen at the stalled state on coarser mesh (not the best practice mesh).
- Lower lift predicted at the stalled state